

The effect of high-ratio biochar replacement in concrete on performance properties

-Experimental study of biochar addition to concrete mixture.

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ABSTRACT

Globally the emissions of carbon dioxide from anthropogenic activities are an issue regarding the future of our planet. Today the building industry is a large contributor with approximately 10 percent of the total emissions coming from energy usage in the building industry, where about 7 percent of the global CO₂ emissions are connected to the cement industry. Since cement is important and today, a non-replaceable material in concrete mixture considering the mechanical properties this is considered as a problem. Concrete is essential to the building and infrastructure industry and therefore it is of great value for society. To be able to lower the impact of concrete manufacturing, different materials are investigated to replace a part of the cement.

Today, alternative materials are implemented in the cement compositions to improve the environmental impact. One material commonly used is fly ash, a waste material from coal combusting industries. However, a renewable and carbon emission sinking product could have a great impact on the total emissions from concrete manufacturing. A product that could be suitable for this is biochar, a product from pyrolysis of biomass. Previous studies show properties that could be desirable in concrete manufacturing such as high specific surface area, low bulk density, low thermal conductivity, and sound-absorbing function. Also, there are studies of biochar in cementitious material with promising results.

To further investigate the biochar impact on concrete this thesis is conducted. A literature review of previous studies of biochar applications and biochar addition to concrete was conducted. This is to analyse the properties of biochar and the effect of the application on the concrete properties. Also, an experimental study was conducted to further analyse the concrete and compare the findings to previous studies.

In this thesis concrete with biochar ratios of 5, 8, and 10 percentages according to the weight of the cement were compared to evaluate the performance properties. This was conducted by a laboratory test where 100 mm cubes were cast and tested for their compressive strength after 28 and 56 days. Other properties which were evaluated were the workability, density, microstructure, and chemical properties.

The result showed that the workability was significantly lower for concrete mixtures with biochar addition. Also, the density decreased as the ratio of biochar increased. The same happened to the compressive strength where the comparison species had a compressive strength of 72 MPa after 28 days and the sample with 10 percent had a compressive strength of 52 MPa. However, the sample with 10 percent of biochar had the highest increase of compressive strength after additional 28 days of curing. The FTIR could not show any significant changes between samples with zero biochar addition and the samples with biochar addition

Keywords: Biochar, Concrete, Sustainability, Cement, Biochar in concrete, Carbon dioxide, Building industry, Micro-structure.

SAMMANFATTNING

Utsläpp av koldioxid är ett globalt problem som hotar framtiden för vår planet. Idag är byggindustrin en stor bidragande faktor till dessa utsläpp där omkring 10 % av de globala utsläppen kan kopplas till energiförbrukningen i byggindustrin. 7% av de globala utsläppen kommer från cementindustrin. Då cement är ett så pass viktigt material och det saknas ersättande material med samma egenskaper anses detta vara ett problem. Betong är grundläggande för bygg- och infrastrukturmarknaden och är därför viktigt för samhället. För att kunna minska påverkan av betongtillverkningen så utreds olika material för att kunna minska cementandelen i betongen.

Idag finns alternativa material som ersätter en del av cementen för att minska klimatavtrycket. Ett sådant material är flygaska, vilket är ett restmaterial från industrier. Att i stället ersätta detta med ett förnybart bio-baserat material med koldioxidsänkande egenskaper skulle kunna innebära en förbättring av de miljöpåverkande egenskaper som finns hos betongtillverkningen. En produkt som skulle kunna vara lämplig för detta är biokol vilket är en produkt från anaerob förbränning av biomassa. Tidigare studier visar att egenskaper som skulle kunna vara fördelaktiga vid betongtillverkning finns hos biokol. Dessa egenskaper är hög specifik ytarea, låg skrymdensitet, låg värmekonduktivitet och ljudabsorberande egenskaper. Det finns även tidigare studier där biokol har applicerats till betong där resultatet har varit lovande.

Detta examensarbete har skrivits för att ytterligare analysera biokolets inverkan på betongen. För att göra detta har en litteraturstudie sammanställts med tidigare studier av biokol och biokolets inverkan på betong. Detta för att analysera biokolets karaktärsdrag och vilka effekter det har på betongens egenskaper. Till detta har även en experimentell studie gjorts för att ytterligare analysera betongens beteende vid applicering av biokol och för att kunna jämföra resultat från tidigare studier.

I detta examensarbete har cementet i betongen ersatts med 5, 8 och 10% biokol av cementets vikt för att kunna jämföra egenskaperna mellan de olika proverna. Detta gjordes genom ett laboratorietest där 100 mm kuber gjöts och testades för tryckhållfastheten efter 28 och 56 dagar. Andra egenskaper som kontrollerades var konsistensen, densiteten och mikrostrukturen genom FTIR test.

Resultatet visade att konsistensen påverkades kraftigt då biokol adderades till betongen. Densiteten minskade desto större andel av cementet som byttes ut. Liknande resultat uppmättes för tryckhållfastheten där den minskade från 71,9 MPa för proverna utan biokol till 51,6 MPa för betongen med 10% biokol, detta efter 28 dagar. Dock så kunde det ses att den största tillväxten av hållfasthet efter ytterligare 28 dagars härdning kunde uppmätas i provet med högst andel biokol (10%). Resultatet från FTIR testet kunde inte visa några tydliga skillnader mellan proverna med och utan biokol.

Sökord: Biokol, Betong, Hållbarhet, Cement, Biokol i betong, Koldioxid, Byggsektorn, Mikrostruktur.

FIGURES

Figure 1: Cellular structure of biochar before and after grinding (Choi et al., 2012).....	8
Figure 2: SEM micrographs of biochar samples (Das et al., 2015b)	9
Figure 3: Strength developing curve for concrete (Byfors, 1980)	12
Figure 4: Crack pattern following the particle surface (Ahmad et al., 2015)	17
Figure 5: Tested specimen a) 0% ratio, b) 10% ratio (Choi et al., 2012).....	17
Figure 6: Result from FTIR test (Akhtar & Sarmah, 2018)	18
Figure 7: Results of IR spectra found by Horgnies et al. (2013)	19
Figure 8: Result of FTIR test on biochar (X. Yang & Wang, 2021).....	19
Figure 9: Forms of slump (SS-EN 12350-2:2019)	22
Figure 10: Crack pattern of a satisfactorily performed test (SS-EN 12390-3:2019)	22
Figure 11: Unsatisfactory failure (SS-EN 12390-3:2019)	23
Figure 12: Concrete mixture	26
Figure 13: Mixture of dry ingredients	27
Figure 14: Spread of slump, 0% biochar addition.....	29
Figure 15: Batch 3 after mixture	29
Figure 16: Set up for measuring the height of the slump test.	30
Figure 17: Compacting of the samples on a vibrating board. (Different test but same procedure, mould, and vibration board)	30
Figure 18: Curing of batch 1-3	31
Figure 19: Testing device for compressive strength	31
Figure 20: Slump test of control batch, 0% biochar	33
Figure 21: Slump test with height difference, a) 5% b) 8% c) 10% biochar.....	34
Figure 22: Average density of samples according to replacement ratio	35
Figure 23: Average compressive strength.....	37
Figure 24: Percental change from first to second test.....	38
Figure 25: Cubes after compression, 0 to 10 % from left.	39
Figure 26: Crack from compressive strength testing, top or bottom.....	39
Figure 27: Result from FTIR, the highest intensity.....	40
Figure 28: FTIR of cement and biochar samples.....	40
Figure 29: Microstructure of biochar and concrete.....	41
Figure 30: Cubes after compression, batch 1 test 1, test 2	53
Figure 31: Cubes after compression, batch 1 test 3, test 4	53
Figure 32: Cube after compression, batch 1 test 5	54
Figure 33: Cube after compression, batch 2 test 1	55
Figure 34: Cube after compression, batch test 2	55
Figure 35: Cube after compression, batch 2 test 3	56
Figure 36: Cube after compression, batch 2 test 4	56
Figure 37: Cube after compression, batch 2 test 5	56
Figure 38: Cube after compression, batch 3 test 1	57

Figure 39: Cube after compression, batch 3 test 2, test 3	57
Figure 40: Cube after compression, batch 3 test 4	58
Figure 41: Cube after compression, batch 3 test 5	58
Figure 42: Cube after compression, batch 4 test 1	59
Figure 43: Cube after compression, batch 4 test 2	59
Figure 44: Cube after compression, batch 4 test 3	60
Figure 45: Cube after compression, batch 4 test 4	60
Figure 46: Cube after compression, batch 4 test 5	60
Figure 47: Cube after compression, divergent cracking.	61
Figure 48: Cube after compression, batch 2 test 1 (56 days).....	62
Figure 49: Cube after compression, batch 2 test 2 (56 days).....	62
Figure 50: Cube after compression, batch 2 test 3 (56 days).....	63
Figure 51: Cube after compression, batch 2 test 4 (56 days).....	63
Figure 52: Cube after compression, batch 2 test 5 (56 days).....	64
Figure 53: Cube after compression, batch 3 test 1 (56 days).....	65
Figure 54: Cube after compression, batch 3 test 2 (56 days).....	65
Figure 55: Cube after compression, batch 3 test 3 (56 days).....	66
Figure 56: Cube after compression, batch 3 test 4 (56 days).....	66
Figure 57: Cube after compression, batch 3 test 5 (56 days).....	67
Figure 58: Cube after compression, batch 4 test 1 (56 days).....	68
Figure 59: Cube after compression, batch 4 test 2 (56 days).....	68
Figure 60: Cube after compression, batch 4 test 3 (56 days).....	69
Figure 61: Cube after compression, batch 4 test 4 (56 days).....	69
Figure 62: Cube after compression, batch 4 test 5 (56 days).....	69
Figure 63: FTIR all tests 0%	70
Figure 64: FTIR all tests 5%	70
Figure 65: FTIR all tests 8%	71
Figure 66: FTIR All tests 8%	71
Figure 67: FTIR of cement and biochar	72

NOTATION

Roman upper-case letters

A_c Cross-section area of specimens for compressive strength

D_{max} Coarsest size of aggregate

F Maximum failure load

Roman lower-case letters

f_c Compressive strength

h Height of cubic sample

k Factor for secondary binder in water to cement ratio

l Length of cubic sample

m_i Weight of aggregate

m_s Weight of the sample

w Width of cubic sample

$w\%$ Humidity of aggregate

w/cr Water to cement ratio

TABLE OF CONTENTS

1.	INTRODUCTION	1
1.1.	Purpose /Aim Objective methodology	2
1.2.	Method	3
1.3.	Scope	3
1.4.	Outline of thesis	4
2.	LITERATURE REVIEW	5
2.1.	Concrete	5
2.1.1.	Sustainability in concrete production	6
2.2.	Biochar	7
2.2.1.	Types of biochar	10
2.2.2.	Biochar application.....	10
2.3.	Biochar-based concrete	12
2.3.1.	Workability.....	14
2.3.2.	Density	14
2.3.3.	Compressive strength	15
2.3.4.	Crack pattern	17
2.3.5.	Fourier-Transform Infrared	18
2.3.6.	Biochar in buildings and construction materials	20
3.	EXPERIMENTAL PROCEDURE	21
3.1.	Procedure of testing according to Eurocode	21
4.	METHOD.....	24
4.1.	Experimental procedure	25
4.1.1.	Equipment	25
4.1.2.	Material.....	25
4.2.	Preparation of the material	25
4.3.	Mixing and casting of concrete	27
4.3.1.	Slump test	29

4.3.2.	Casting and curing	30
4.4.	Testing of the samples.....	31
4.5.	Fourier-Transform Infrared.....	32
5.	RESULTS AND ANALYSIS	33
5.1.	Fresh concrete	33
5.2.	Density	34
5.3.	Compressive strength.....	36
5.4.	Cracking.....	39
5.5.	Fourier-Transform Infrared.....	40
5.5.1.	Scanning electron microscope	41
5.5.2.	Carbon dioxide emissions.....	42
6.	DISCUSSION.....	43
7.	CONCLUSION.....	46
i.	Appendix A.....	52
ii.	Appendix B.....	53
iii.	Appendix C	70

1. INTRODUCTION

Today, sustainability is a widely used term with major influences in all areas of human life. As a global initiative, the member countries of the United Nation during 2015 agreed to Agenda 2030 as a directive to work toward a sustainable future. The goals are today applied in many sectors and are well known. Among the global goals according to Agenda 2030 climate action is one with a significant connection to the building industry.

Sustainability in the building industry

The building industry has been detected as a large source of emissions, with about 38 percent of the global emission, seen from process and industry 10 percent of the total emissions can be directly connected to the usage of energy in building construction. This includes the manufacturing of building materials such as cement and steel which has the largest contribution to the total emissions (UN & iea, 2019). Roughly estimated, each ton of cement produces about 0.65 to 0.95 tonnes of CO₂ (Müller & Harnisch, 2008), and where the high volumes of cement contribute to about 7–8 percent of the world's yearly global CO₂ emissions (Lehne & Preston, 2018; K.-H. Yang et al., 2015). Among the global goals according to Agenda 2030, climate action is one of the goals mostly affected by the emissions from the building industry. According to this goal, the global emissions must be decreased 45 percent from 2010 to 2030 to reach the set goal of a maximum 1.5°C increase of the global temperature (United Nations, 2021), which is a large incitement to use renewable resources for the development of concrete. Still, the emissions from the building industry are rising. From 2010 until 2018 the emissions had increased 7 percent. According to UN and iea (2019), the emissions must decrease 8 percent yearly from 2019 and forward. This is to be able to reach the goals according to Agenda 2030.

Meanwhile, the population is predicted to increase by about 2.5 billion during the next 30 years which means that there will be a demand for new residential and infrastructures in the future. To be able to proceed with the building expansions and development of new structures, several improvements can be applied. According to UN and iea (2019) buildings with net-zero emission and net-zero energy should be implied in guidelines for future constructions. Improvements regarding the building materials are needed. An estimation of the building material's contribution to emissions can be done through lifecycle analysis. Another example to improve sustainability is to develop innovative low-carbon materials and the implementation of the design and construction process (UN & iea, 2019).

The enlarged utilization of concrete has forced manufacturers to develop building materials that are more sustainable (Behl et al., 2021). In recent years there have been different research projects to replace a part of the binders in concrete with different types of waste materials such as husk ash, waste glass, and waste in general (Lehne & Preston, 2018). Lately, studies have been done where the replacement of the binder in concrete has been biochar. The previously conducted studies have replaced the cement with about 0.08 to 5 percentages with biochar

and even up to 8 and 20 percent (Choi et al., 2012; Mensah et al., 2021). The biochar addition in construction materials could even be used to store CO₂ in the structural components of the building (Sirico et al., 2021). Dixit et al. (2021) claim that one kg of biochar used in concrete can store about 2.5 kg CO₂ emissions. However, there has been found that not only the carbon emission retaining properties are of interest for applications in concrete manufacturing. Properties such as high porosity and high specific surface area have also been found as suitable (Dixit et al., 2021).

Most of the studies that previously have been conducted have focussed on biochar instead of concrete. This has led to that the production of biochar has been the focus more than the production of the concrete itself. This thesis attempts to remedy that by examining the effect of biochar on the performance properties of concrete.

1.1.Purpose /Aim Objective methodology

The objective of this master thesis has been to evaluate the specific properties of concrete when replacing higher proportions of cement with biochar. It has been noted that there is a lack of studies regarding larger replacement ratios (>8%) of biochar in concrete. This thesis aims to perform studies of the biochar's effect on the concrete's mechanical properties when a larger ratio of the cement is replaced during the casting. The importance of this is the environmental perspective since the replacement of a larger amount of cement with biochar will improve the sustainability of the concrete. The study is based on laboratory tests that mainly focus on the mechanical changes that occur in the concrete when adding biochar.

Properties of particular interest were the workability of the fresh concrete and the compressive strength. This is to obtain data on the difference between the result from different ratios of biochar application.

The result of the laboratory studies has mainly two applications, partly to be able to compare the found results to previous studies of biochar applications in concrete and collect data for further research. The following are the research questions:

- What are the properties of biochar and how do they act in a cementitious composition?
- How is the compressive strength of cementitious materials affected by adding biochar?
- Are the previous studies able to compare with the result of this thesis?
- How is the workability affected when adding biochar to the cement mixture?
- What is causing the change of properties of cementitious materials when adding
- biochar?

1.2.Method

A literature review is done with the purpose to present the environmental issues there are today connected to cement and concrete production. The review aims to enlarge the understanding of concrete as a building material and the connection to the environmental impact. The review will also cover the production and properties of biochar and its application to concrete according to previous studies and experimental implementations.

An experimental study with elements according to Eurocode is performed to analyse the implementation of biochar to the concrete. A comparison to previous studies and an analysis of the result from larger replacement ratios will be conducted.

The method adopted to prepare the concrete samples has been chosen according to traditional casting methods. This is since there is an accepted method for the construction and building industry. Additionally, it is an advantage of the research that the development of a new product can be implemented without changing the manufacturing technique. This contributes to a product that can easily integrate with existing processing methods

1.3.Scope

When introducing new concrete mixes to the market, a various number of tests must be performed. The tests could for example include resistance to freezing and also the air content in fresh concrete. In this study, those parameters and others have not been included, mainly since those steps of the process of creating a new type of concrete are performed later in the process. The research in this master thesis is more early in the procedure where the possibility of biochar addition is analysed.

Other properties which will not be included are the properties of the young concrete (curing less than 28 days), nor the aged concrete (longer than 56 days of curing).

The properties of the biochar concrete could change during aging. The time of this project limits the possibilities to evaluate the properties of the concrete suffered from aging and decomposition from the climate.

Other properties essential in building constructions are fire resistance and acoustic, although, tests in that field will not be covered in this study.

1.4. Outline of thesis

The thesis is formed as:

- Chapter 1 Includes the background and an introduction to the topic. It also includes the purpose of the thesis together with the aim. The chosen scientific approach is presented here, also, the content of the thesis.
- Chapter 2 Includes the literature studies including previous studies, both theoretical and experimental. The analysed studies mainly focus on the findings of biochar research and the properties of biochar. This together with previous research of biochar implementation to concrete.
- Chapter 3 describes the experiment, here the method of the experiment in the laboratory is presented.
- Chapter 4 Describes the procedure of the laboratory work
- Chapter 5 Presents the result and analysis of what has been found by the experiment
- Chapter 6 Presents a discussion of the found results and the literature
- Chapter 7 Presents the conclusion and recommendation for further research

2. LITERATURE REVIEW

In this chapter, a compilation of present literature is presented. First, the problems connected to the concrete industry and a short coverage of the actions to resolve those until today are introduced. An introduction to biochar and its application follows, together with usage in composite material, and a compilation of previously reported results is conducted. At last, a calculation of carbon dioxide emissions from concrete production due to the replacement ratio is calculated.

2.1. Concrete

Concrete is one of the most used construction materials (Gursel et al., 2014) where it is highly used in building construction globally and is also associated with high carbon emissions (Crow, 2008; Gursel et al., 2014). It is a fabricated material, and Crow (2008) described it as “the single most widely used material in the world” where the most common application of the material is in infrastructure and building projects. Concrete is a composite of cement, sand, aggregate, and water, often with added chemical substances to provide desired properties. When the cement is reacting with water it is forming a glue-like medium between the materials that are essential to bind the constituent materials of the concrete (Sveriges Byggindustrier, 2016). Globally there is a concrete consumption of around 20 – 25 billion tons each year ((Sirico et al., 2021)-(Gursel et al., 2014)). The large-scale production is mainly connected to the properties where concrete is an attractive building material for both buildings and infrastructures (Crow, 2008). Properties which is also desirable and found in concrete are, for example, low production costs, ease of transport, high durability, and relatively good fire resistance (Gursel et al., 2014). To produce one ton of Portland cement approximately 1.22 tons of limestone and 0.31 tons of clay are required, both non-renewable materials. Also, the non-renewable case includes the aggregate, which means that the main parts of essential composites in the concrete are non-renewable resources (Sirico et al., 2021).

The cement supply is essential for all present and future production of infrastructure projects, the consumed volume is large, but the cement is not endless. Today there is no existing material to replace the clinker and cement material in concrete manufacturing (Regeringskansliet, 2021) despite that, it is essential for concrete production. During the summer of 2021, a national crisis occurred in Sweden when Cementsa, the only clinker provider in Sweden, was about to be shut down from its operation at the Slite site in Gotland. This was because of a decline in the permit application. The consequences of a decline to extract clinker would have an impact on the Swedish building sector and the entire infrastructure (Björkman, 2021). The Slite site is providing Sweden with approximately 75% of the cement usage (Industriarbetsgivarna, n.d.). At last, the permission got extended until the end of 2022. However, it could be seen from this event that the cement industry has future issues to handle.

There are different types of cement. Portland cement, one of the most common types of cement contains a mixture of limestone and clay or shale. The clinker makes up about 65 percent of the cement weight (West et al., 2017), where the production of the clinker has the highest environmental impact on the production chain in making concrete. A life cycle analysis shows that the clinker makes up about 90% of the CO₂ emissions (Svensk Betong, 2017). In Portland cement, 50 percent of the emissions are connected to the combusting of fossil fuel in the production process (Gursel et al., 2014). Because of the high emissions from cement production, it could be clear that with a reduction of cement to the concrete, the levels of CO₂ could be reduced. The cement ratio in the concrete mixture depends on the type of concrete required for the specific project, typically between 7 and 12 percent of the concretes volume (PCA, n.d.). During 2020 the estimated cement production was 4.1 billion tons (U.S. Geological Survey, 2020), a level that has been kept since 2013 where the cement production has exceeded over 4.0 billion tons every year (Garside, 2021a). Still, there are expectations in the industry that the usage of cement will increase to around 5 billion tonnes by 2030 (Müller & Harnisch, 2008), an approximately 25 percent increase. With an increased cement production of about 25 percent, the emissions from the cement production would have an even higher impact on the total CO₂ emissions globally.

The actual emission of one ton of cement is not determined to a certain level. However, Gursel et al. (2014) claimed that one ton of Portland cement produced caused 0.87 tonnes of carbon dioxide emissions. Mensah et al. (2021) presented numbers for one ton of cement, where one ton of CO₂ is released. Akhtar and Sarmah (2018) present the value of 0.95 tons of CO₂ per ton of cement. To determine a reliable level of emissions, a mean of these values is calculated. The value of 0.94 tons of carbon emissions per tonne of cement is calculated to the mean value.

2.1.1. Sustainability in concrete production

From 2017 the CO₂ emissions from the cement industry have decreased by approximately 20 percent during a period of 20 years, mainly from the cement industries adopting the composition of the material with lower proportions of clinker and the usage of more sustainable binders than cement. Still, there is room for improvements in production. In the coming years, concrete manufacturing is predicted to decrease its carbon dioxide footprint by about 20% and still satisfy the demands for construction built on the land. The greatest possibility of optimizing has been detected in the housing construction industry. (Svensk Betong, 2017)

Today, there is no product on the market which could replace cement that has the same categorization and cost efficiency (Campos et al., 2020). However, the concretes impact on the environment can be lowered by optimization in different ways, mainly by reducing the proportion of cement clinker. The optimizing level is highly dependent on the demand of the concrete properties. One technique that is used today to obtain lower ratios of cement in

concrete is to lower the clinker material and replace it with waste productions from industries. Such materials could be fly ash (steel industry) or slag (Svensk Betong, 2017). The fly ash strengthens concrete when added in certain portions, and it also affects the air and water content of the concrete due to the high carbon content and negatively impacts its workability (Choi et al., 2012). Behl et al. (2021) on the other hand found that the addition of fly ash improved the workability and therefore allowed the water content to be lowered. This was explained as the shape of the particles reduced the friction in the paste. It was also found that the highest compressive strength was obtained when five percentages of the cement were replaced. Higher replacements gave a decrease in compressive strength (Behl et al., 2021).

Other replacement materials of the cement could be plastic, glass, and waste from construction and demolition (Sirico et al., 2021). Also, a replacement product could be renewable biobased materials (Svensk Betong, 2017) such as biochar. Lately, research in the field has been done when biochar has been used as a filler material or to replace a part of the cement (Sirico et al., 2021).

A life cycle analysis of biochar produced in the Philippines performed by Campos et al. (2020) showed that a replacement of cement with biochar to concrete mixes could improve the environmental and health impact regarding toxicity in water, soil, and air, ozone formation, and depletion and hazardous waste. Also, data is presented where the impact of global warming could be seen to decrease. It was also suggested in the thesis, that the biochar could replace the fly ash. The analysis was performed as cradle to gate, which covers the materials life cycle from that it leaves the manufacturer to that it reaches the factory gate. The steps presented in the study are raw material- material processing- production and transportation (Campos et al., 2020).

2.2.Biochar

Biochar is a product of pyrolysis of organic material or also called biomass. To create biochar biomass is heated in an anaerobic environment procedure with high temperatures. The anaerobic procedure is also called pyrolysis which transforms the biomass into a carbonaceous material. Other processes to produce biochar are, for example, hydrothermal carbonization, gasification, and torrefaction (Yaashikaa et al., 2020). According to the European Biochar Certification (2012), the definition of biochar requires pyrolysis temperatures between 350 °C and 1000 °C.

Biomass and organic plant-based materials are built up by cells (Das & Sarmah, 2015). The material consists of long parallel fibres with cylindrical shapes as there can be seen in Figure 1 below. A main contributor to the cell walls is cellulose, land-living plants are also often built up by lignin and also, pectin and hemicellulose between the cell walls (Nationalencyklopedin, n.d.). Pyrolysis is a procedure where the organic material is burned under conditions where no oxygen is present (Dhyani & Bhaskar, 2018). Organic polymers such as cellulose, pectin, hemicelluloses, and lignin will start to break down during the pyrolysis due to high

temperatures where the polymers will start to depolymerize in anaerobic conditions and extractive chemical bonds will be created together with tars and volatiles (Das & Sarmah, 2015).

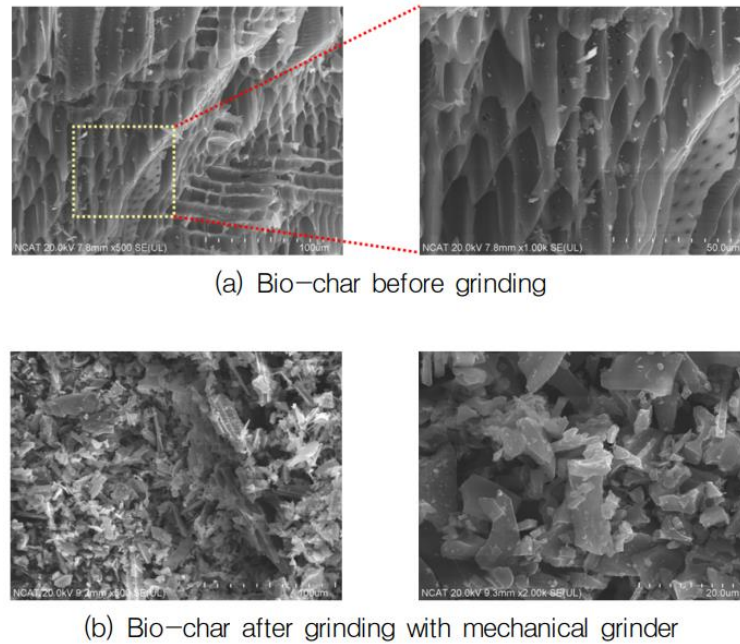


Figure 1: Cellular structure of biochar before and after grinding (Choi et al., 2012).

During the pyrolysis, the temperature varies where different temperatures will give different reactions of the biopolymers exposed to the pyrolysis. An experimental study by H. Yang et al. (2007) showed that pyrolysis between 220–315 °C gave a decomposition of hemicellulose, at 315– 400 °C the cellulose decomposed and that the lignin decomposed in the larger range of 160 – 900 °C. From the procedure vapor of fragments of the biopolymer is produced from the biochar consumed during the pyrolysis. Also, there is a release of CO₂, CO, and, CH₄. Some of these vapours can be condensed and collected to bio-oil, which is a bi-product of the pyrolysis process. Non-condensed materials can instead be used as the heat source of pyrolysis (Dhyani & Bhaskar, 2018). The proportions and quantities of the bio products from pyrolysis depend on the pyrolysis process, source of bio material, temperature, etc (Ndirangu et al., 2019).

Biochar is a product with low or no addition to greenhouse gases. If the biomass is produced from raw materials such as plants, biochar production can be considered carbon neutral. CO₂ emissions from biochar production can be absorbed by plants, plants that can grow, and later be used for producing new biochar. Depending on feedstock and pyrolysis conditions biochar can store high content of CO₂ (Cuthbertson et al., 2019). There are examples where the procedure even could be considered as a CO₂ sinking production, which could occur if the biochar is produced from waste materials (Das et al., 2015a). The usage of waste materials also contributes to more sustainable waste management. Since different properties in the material occur as a consequence of the production, there are different types of biochar suitable for

different applications (Srinivasan et al., 2015). European Biochar Certification (2012) has published a list of “permissible biomasses for the production of biochar” with information about special requirements and information to consider in the production.

The quality of the biochar is characterized by the properties retrained from the feedstock and the production process (EBC, 2012). The procedure of pyrolysis creates a material that has high carbon content in comparison to hydrogen and oxygen. This indicates a material with a high carbonization grade and chemical stability (Gupta et al., 2020; Sirico et al., 2021). Spokas (2010) proposes that a ratio of carbon to oxygen which is equal to 0.2 is having a half time of over 1000 years, further, ratios between 0.2 to 0.6 have a half time of 100– 1000 years whereas lower ratios indicate more stable carbon.

Other properties found in biochar are high specific surface area, high pore volumes, and good absorption capacity (Sirico et al., 2021). The high specific surface area can be observed in the particle microstructure, where the microstructure can be seen as cellular or irregular where the structure is depending on the feedstock (Choi et al., 2012). Das et al. (2015b) studied the mechanical properties of different sources of biochar where they presented SEM micrographs of different biochar samples (Figure 2). From the figure, it can be seen for example an irregular shape of the PSD (landfill pine sawdust, one step auger) samples and a cellular structure of the TCP (landfilled pine sawdust, two-step auger) sample.

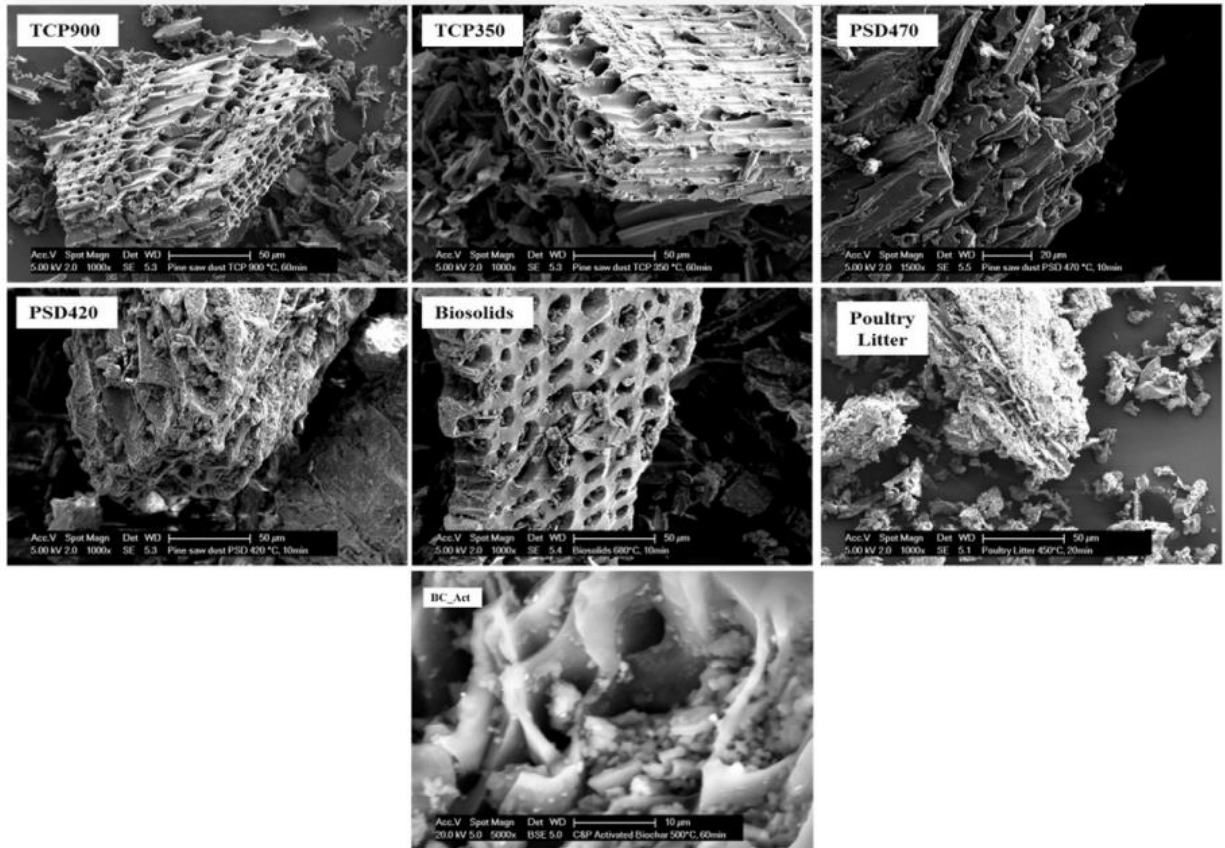


Figure 2: SEM micrographs of biochar samples (Das et al., 2015b)

2.2.1. Types of biochar

There have been studies of different sources of biomass and pyrolysis temperature's effect on the biochar (Kloss et al., 2012). As an example, it could be seen that biochar created in lower pyrolysis temperatures ($<400\text{ }^{\circ}\text{C}$) tends to become more hydrophobic (water-repelling) than biochar created in higher temperatures, and this is due to hydrophobic surface characteristics depending on hydrophobic functional groups from tars (Das & Sarmah, 2015). The properties found in biochar could make it suitable for different applications, some of its properties are high absorption ability and anti-microbial properties (Das et al., 2016), where the microstructure of the biochar particle also affects the absorption ability (Choi et al., 2012). Das et al. (2015) showed that the mechanical properties were more dependent on the temperature of the pyrolysis rather than the duration. This was done with a test where the same raw material was exposed to different temperatures during the same time period. Also, Srinivasan et al. (2015) listed the pyrolysis conditions as a main factor of the biochar properties, but also the source of the biochar.

Das et al. (2015) showed that it could be proven by experimental analysis that the biochar diverged in behaviour, depending on previously mentioned factors such as pyrolysis temperature, feedstock, and duration. The biochar in the study was produced from different sources such as broiler litter (poultry litter), dewatered pound sludge, and, dissolved air floatation from chicken farm industries, sources that also were investigated were paunch grass, sewage sludge, and pine sawdust. The result of the study showed that pine sawdust had the highest carbon content (91 percent), and the lowest carbon content was found in the paunch grass (65 percent). The pine sawdust biochar also showed the highest specific surface area due to the same pyrolysis conditions as the other materials. The carbon content in biochar also depends on the temperature of the pyrolysis, Choi et al. (2012) presented that a temperature deviation from $300 - 800\text{ }^{\circ}\text{C}$ could increase the percental amount of carbon from 56 – 93 percent, temperatures above this level did not affect the content of carbon, although, continued to reduce the yield of biochar.

2.2.2. Biochar application

Because of its properties biochar has many applications in different fields such as agriculture, various industries, and soil amendment (Kloss et al., 2012; Sirico et al., 2021). The material properties such as high porosity, water holding capacity and, the possibility to fix fractions of carbon have shown to be desirable, especially in agriculture where the growth has increased together with the crops possibilities to provide its nutrition (Campos et al., 2020; Sirico et al., 2021). The water holding capacities of biochar is high, where the biochar can absorb high volumes of water (Cuthbertson et al., 2019). The improvement of the nutrition and the increase of crop productivity is depending on the pH change and change in the structure of the soil, which leads to an improvement in the efficiency of the fertilizing. Even though the positive effects of adding biochar, there are some risky aspects when adding biochar from contaminated sources (McHenry, 2009; Ndirangu et al., 2019). According to Lehmann (2007),

biochar produced under 400 °C could be non-suitable for soil amendments and improvements of the fertilizing due to its low surface area and pH value.

Aside from other properties, the capacity of storing carbon dioxide has made biochar especially interesting as a construction material. This together with low thermal conductivity, porosity, low bulk density, and sound absorptive properties (Cuthbertson et al., 2019). Compared to cement production the carbon dioxide emissions are low. From one tonne of feedstock due to biochar production is approximately 0.57 tonnes of CO₂ is released (X. Yang & Wang, 2021). The density of the biochar is depending on which source has been used in the production and also the pyrolysis process (Sirico et al., 2021). By experimental studies, Sirico et al. (2021) determined the bulk density of the biochar to $0.38 \pm 0.01\text{g/cm}^3$ and the true density to $2.04 \pm 0.01\text{g/cm}^3$. The porous structure and water holding properties is affecting the workability of the concrete during the casting procedure. The water-holding property is creating a longer curing time where the concrete can develop its strength in a secondary step by curing through reaction to the water released later in the curing time (Sirico et al., 2021). Because of the water holding capacity the carbon addition to the mixture will require higher ratios of water which will cause a reduction of the compressive strength. The decrease of strength will be enlarged with a higher water to cement ratio (Choi et al., 2012).

Mensah et al. (2021) present a review of previous studies where the price is various, the cost efficiency of biochar varies with the type of production and feedstock. The authors is mentioning that the market price is \$184 per tonne compared with the cement price of \$124 per metric tonne during 2020 in the U.S. (Garside, 2021b). However, the price can vary. Akhtar and Sarmah (2018) is noting that the price also depends on the scale of the production whereas biochar from straw differ from \$399 to \$181 per tonne produced depending on if it is medium-scaled or large-scaled production. The author is also mentioning that the price depends on which source has been used as feedstock.

Previous studies about how biochar affects concrete properties have been presented (Campos et al., 2020). The studies are few and many of them are focused on low proportions of biochar. Akhtar & Sarmah (2018) claims that there have not been any studies of biochar additions in concrete, which is not completely correct. For example, Choi et al. (2012) replaced cement with biochar in mortar mixtures, but still, it shows that there have not been too many previous studies of the biochar addition to concrete.

When developing concrete there can be seen as a big step between laboratory findings and the applications in real structures. One reason is that the variability of the materials is essential for the product, and one has to be certain about those variabilities (Crow, 2008). This means that the contents of the biochar must be certain. The ratio between oxygen and carbon content in the biochar could also be important for the application of biochar to concrete. The lower the ratio is, the more stable the carbon is. A lower ratio is claimed to be more suitable for concrete applications (Dixit et al., 2021).

2.3.Biochar-based concrete

Different studies have been done on the field of biochar concrete. In this section results of previous studies are presented. First, a general presentation of the findings in previous studies is presented, which is then followed by a detailed section where previous studies of workability, density, compressive strength, and crack behaviour are presented.

The previous studies show that biochar has properties that concrete manufacturing could benefit from such as reducing the early risks of cracking in concrete (Dixit et al., 2021), reducing carbon dioxide emissions (Cuthbertson et al., 2019; Das et al., 2015a; Dixit et al., 2021), and in some cases increase the flexural strength when replacing the cement or fine aggregates in smaller proportions (Ahmad et al., 2015; Gupta et al., 2020). By adding biochar, the workability is directly affected, and the compressive strength is most likely to decrease when adding higher ratios according to previous studies.

The standard procedure is to measure the properties of hardened concrete after 28 days, since it is common knowledge that concrete is developing most of its strength during this period this can be seen in Figure 3. The curve of strength gain will be flattened after this period and the properties will not change significantly. However, addition of biochar has been seen to make the concrete diverge from this predicted pattern. This is since water absorption abilities and holding capacity have been denoted as properties of the biochar. This gives the concrete conditions to cure during a longer time span and has been seen to develop strength even after the 28 days (Choi et al., 2012). Choi et al. (2012) performed an experiment where cast mortar and concrete samples with and without biochar additions were weighted several times during a time span. There, the authors could see that the samples of the concrete without biochar addition had a higher percental weight loss over the tested period of 28 days. This shows that the biochar addition gives the concrete a water-holding property.

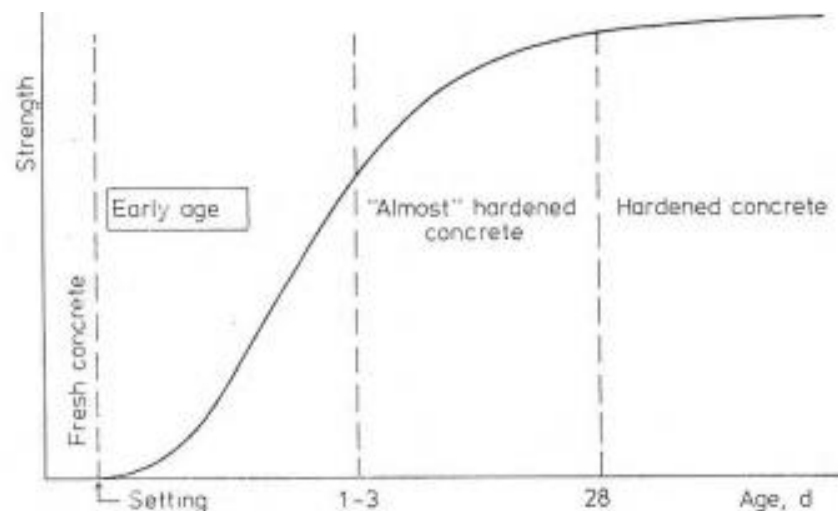


FIG 1.1 Schematic picture of the hardening process.

Figure 3: Strength developing curve for concrete (Byfors, 1980)

Mainly the studies which have been compared in this thesis are based on those where a part of the cement has been replaced with biochar. Alternatively, others such as Praneeth et al. (2021) replaced the fine aggregates with biochar. The study showed that the thermal conductivity of the concrete was lowered when adding 10 and 20 percent of biochar, while the thermal conductivity did increase when adding 40 percent in such a way that it exceeded the control specimen. It was also found that by replacing the aggregates with 10, 20, and 40 percent of biochar the compressive strength was decreasing while the flexural strength increased when the replacement was up to 20 percent and then decreased with higher replacements. Similar findings were reported by Gupta et al. (2020) where the cement was replaced instead. Here the replacement ratio was smaller, i.e., 0.5, 1 and, 2 percent of the cement was replaced which gave an increase in the flexural strength with 4.4, 2.9, respectively 1.2 percentages compared to samples with no replacing of biochar. Ahmad et al. (2015) could also see an improvement in flexural strength when adding pyrolyzed bamboo particles.

Dixit et al. (2021) have investigated the properties of biochar in combination with ultra-high performance concrete. Since ultra-high-performance concrete has lower water to cement ratio than standard concrete the shrinkage during the curing is affected and increases the risks of cracking in the early stage. The water holding capacity detected in biochar could prevent these problems by storing internal water in the concrete when hardening.

An experimental analysis of different biochar sources performed by Akhtar & Sarmah (2018) where the feedstock was poultry litter, pulp, paper mill sludge, and rice husk could determine some properties of the biochar concrete. The study focused to determine the strength and properties of concrete with biochar content. It was found that the poultry biochar had a progressive impact on the flexural and splitting tensile strength, meanwhile, it also had a reducing effect on the compressive strength. The pulp and paper mill sludge had an increasing effect on the mechanical properties as it replaced 0.1 percent of the cement whereas the replacement with poultry and rice husk increased the flexural strength by over 20 percent.

Gupta et al. (2020) conducted a study where the size of the particle was regarded of importance. Particles finer than 100 μm is argued to generate a filler effect and particles in a size larger than 10 μm will give reason to the internal curing which gives rise to the later increase of strength. The study is mainly to evaluate the concrete after it has been subjected to high temperatures 300–550°C. However, in this thesis, the compared result is from those tests which had not been exposed to any external heat sources.

Sirico et al. (2021) did a study of cement replacement from biochar of wood waste. The replacement ratios were 2.5, 5, 7.5, and 10 percent. Sirico et al. (2021) state that the addition of about 1 percent of the cement weight could improve the mechanical properties of the concrete while a higher replacement ratio could decrease the mechanical strengths.

Another property that can be affected due to biochar application is fire resistance. Gupta et al. (2020) could show that an addition of 2 percent biochar made from wood waste in concrete could impact the resistance of the concrete exposed to high temperatures. According to the study it was found that the damage of the microstructure from the addition of 0.5 and 2 percent of biochar to cement also led to 16 respective 9 percent increase of compressive strength.

2.3.1. Workability

The porous structure of the biochar particle causes high water absorptions, which will impact the workability (Choi et al., 2012). By laboratory tests, Choi et al. (2012) tested the workability of mortar mixtures through a “flow test”. The test was done on samples with 5, 10, and 20 percent replacement of biochar. The addition of 20 percent was reported as “impossible to measure the percentage of flow properly”. Choi et al. (2012) concluded that an addition of 5 – 10 percentages of biochar replacement was comparable to an addition of 20 percent of fly ash, also stating that this could depend on the biochar type and the “level of ignition”. Sirico et al. (2021) performed a laboratory test where they based the workability consistence classes according to EN 206-1. To obtain the right consistency a slump test was performed and a superplasticizer Mapei Dynamon Xtend W202R, was added in proportion to obtain the desired values from the slump test. The concrete had the water to cement ratio wcr equal to 0.5. The proportion of biochar in the study was 2.5, 5, 7.5, and 10 percent. The slump test for the ratio up to 7.5 percent was possible to retrain results according to consistency class S4, the batch with 10 percent could only reach consistency class S1 “with a reasonable amount of superplasticizer”.

Adding the biochar to the mix will impact the workability since experimental studies show that the biochar is acting as moisture absorbent, therefore a fluid concrete will be more workable when adding the biochar than a dry, more firm mix.

Through an experimental study by Cuthbertson et al. (2019) where the sand or the aggregates were replaced with biochar, the authors state that one kg of biochar could require one liter of additional water. It was also found by the author that the amount of water that could be added before the biochar stopped to absorb the water was about 650 ml per kg biochar.

2.3.2. Density

Sirico et al. (2021) show numbers that indicate that the density was decreasing when the biochar replacement in the concrete was increasing, it is stated in the paper that the biochar’s influence on the density is limited. It was found that when the cement was replaced with 10 percent, the density decreased approximately 5 percent. Also, Cuthbertson et al. (2019) present data that shows that the density is decreasing with an increase of the biochar ratio where the sand or aggregates was replaced.

2.3.3. Compressive strength

Sirico et al. (2021) found that the addition of up to 5 percent of biochar could increase the compressive strength when the specimen is cured under wet conditions. In the same experiment, there was observed that a higher percent of 7.5 and 10 gave a decrease of 19 respectively 33 percent. Sirico et al. (2021) also found that there were more beneficial to cure the specimen during dry condition regarding the strength development with biochar replacements of 2.5 and 5 percent. In opposite Choi et al. (2012) shows results of lowered strength development in dry curing, here with replacement ratios of 5 and 10 percent.

Dixit et al. (2021) performed tests of compressive strength of ultra-high-performance concrete with an addition of calcinated clay and biochar to investigate the changes in the concrete according to resist cracking at an early age. In the study, the authors found a decrease of around 13% of compressive strength when replacing the cement with 2 and 5 percent biochar. The lowered compressive strength is explained by the particles of biochar than the replaced particles and therefore are creating weak spots in the concrete. The author also suggested that the porosity of the biochar particles decreases the compressive strength and hardness. However, the tests which were done when only clay was added showed similar results to concrete with biochar addition.

Akhtar & Sarmah (2018) presented results that showed a reduction of the compressive strength for all the replacement ratios in the study. By analysing the figures presented in the paper there could be seen that the highest compressive strength was found when 0.1 percent of the cement was replaced with biochar. This was the case for all the different biochar sources (poultry litter, rice husk, and paper mill sludge). Higher additions than 0.1 percent decreased the compressive strength.

A compilation of previous studies was done by Mensah et al. (2021) where the compressive strength of different samples with biochar addition is presented. The compressive strength presented in this study has a range between 33 and 97 MPa and with the biochar addition of 0.1 and 0.08 respectively percent replacement. This is indicating that the biochar application can provide cement-based mixtures with a variety of strengths.

As there are different results found by different authors, the results of selected previous studies of the compressive strength have been collected according to Table 1. Together with Table 2, there is aimed to present a survey of some of the findings.

Table 1: Description of previous studies on compressive strength regarding the method, biochar source, and other data.

Author	Approach	Comparison strength [MPa]	Biochar sources
Akhtar and Sarmah (2018)	Biochar addition to concrete mixture. Performed tests of compressive strength on cylindrical-shaped specimens. Different sources of biochar, comparison after 7, 14, and 28 days. Moist curing of samples	38.5 (estimated)	Poultry litter (PL), rice husk (RH), pulp and paper mill sludge (PP)
Gupta et al. (2020)	Various experiments on different sources. Biochar was produced during slow pyrolysis, ramping rate: 10°C. The particle size varied from 3 to 50µm with $d_{50} = 11\mu\text{m}$. The water to binder ratio was changed to depend on both biochar and cement. Wet curing.		Mixed wood sawdust
Sirico et al. (2021)	Replaced cement with biochar in standard concrete recipe up to 10 percentages. The properties of fresh and hardened properties were investigated together with the internal matrix.	40 MPa water-cured; 35 MPa dry-cured (estimated)	Wood waste
Choi et al. (2012)	Applied to mortar mix with fine aggregates. Hardwood char from slow pyrolysis, grinded to fine particle size. 50 mm cubes. Wet and dry curing.		Hardwood char

The studies mentioned above showed compressive strength results according to Table 2 below.

Table 2: Compressive strength changes in biochar concrete due to biochar addition.

Author	wcr	Source	Curing	0.1%	0.25%	0.5%	0.75%	1%	2%
Akhtar and Sarmah (2018)*	0.32	PL	Moist	-14%	-38%	-25%	-23%	-27%	-
		RH	Moist	-10%	-48%	-22%	-32%	-25%	-
		PP	Moist	-4%	-	-21%	-	-27%	-
Gupta et al. (2020)*	**0.4	Mixed wood sawdust				15.8%		9.9%	9.1%
Author	wcr	Source	Curing	2.5%	5%	7.5%	10%	15%	20%
Sirico et al. (2021)	0.5	Wood waste	wet	5%	3%	-19%	-33%	-	-
			dry	25%	17%	-	-	-	-
Choi et al. (2012)*	0.5	Hardwood	Wet	-	6.4%	-	-5.5%	-20.8%	-40.7
			Dry	-	1.9%	-	-38%	-	-

* The percent has been calculated by the author based on presented data in the paper which the result has been obtained.

** The wcr was not constant since the water/binder (cement and biochar) ratio was used.

2.3.4. Crack pattern

Ahmad et al. (2015) examined biochar composite cement with bamboo feedstock (pyrolysis 850 °C) with different treatments. It was found by field emission scanning electron microscopy that the carbonized particle could change the crack pattern where the crack path is following the contour of the particle which changes the direction of the crack making the cracking of the concrete more energy-consuming. Ahmad et al. (2015) identified a possibly weak interaction between the biochar particle and the cement due to a lack of presence of cement paste onto the biochar particle as seen in Figure 4.

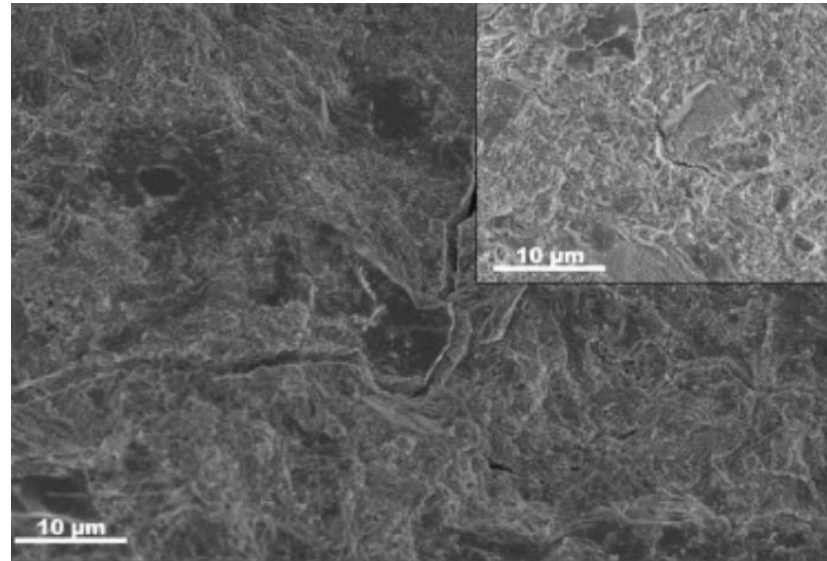


Figure 4: Crack pattern following the particle surface (Ahmad et al., 2015)

Choi et al. (2012) found that the shape of the compressive tested specimen differed between the control sample with no addition of biochar and the sample with biochar additions. The cone shape became less well-defined which can be seen in Figure 5 below.

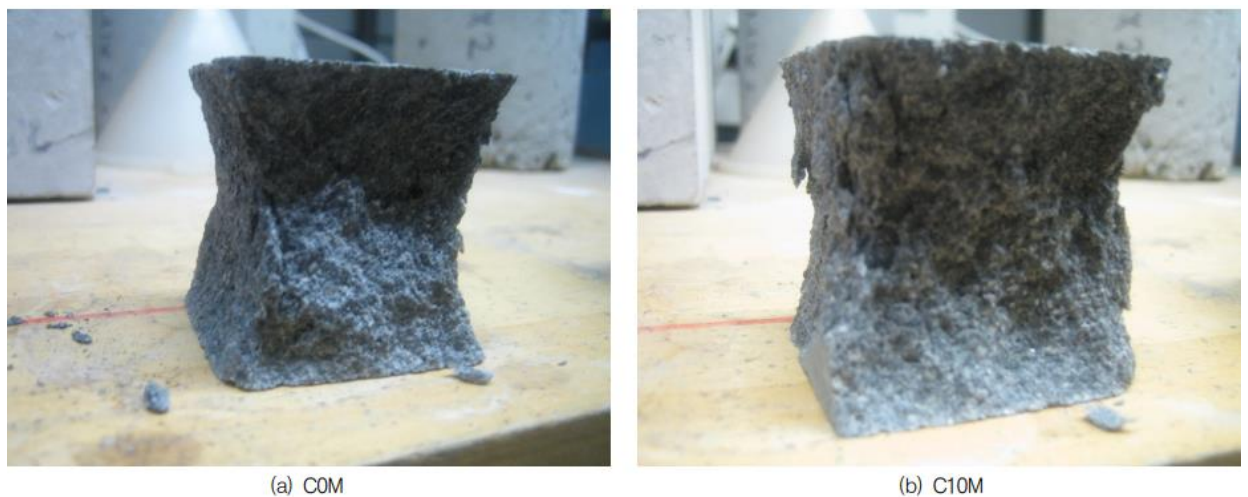


Figure 5: Tested specimen a) 0% ratio, b) 10% ratio (Choi et al., 2012)

Sirico et al. (2021) used scanning electron microscopy to evaluate the concrete mixture. It was found that the particles of biochar were surrounded by concrete and that no separation was detected between the particle surface and the concrete.

2.3.5. Fourier-Transform Infrared

To determine what causes the increases in compressive and tensile strength that some of the studies show, an analysis of the chemical properties can be performed. By studying cementitious materials through Fourier – Transform infrared spectroscopy the concrete can be further analysed. Results from FTIR are shown as a plot that corresponds to the frequency between the bond of pairs of molecules, as a result, there can be seen peaks of the plot according to different wavelengths which are connected to certain pairs. The test is time effective and can tell which substances are present in the sample (Horgnies et al., 2013). The FTIR can also disclose surface functional groups of the sample, and molecular bonding can also be analysed since different wavenumber from the infrared is affecting different bonding. The peaks which can be seen as a plot with the result from an FTIR test reveal the amount of the material which it is indicating (Termo Scientific, n.d.). Akhtar and Sarmah (2018) performed tests through Fourier transform infrared spectroscopy (ATR-FTIR) to determine the variation of functional groups and to be able to characterize the different samples. The samples on which they performed the tests were concrete mixtures with a comparison mixture and three different mixtures with biochar from poultry litter, rice husk, and, paper mill sludge was used to replace parts of the cement.

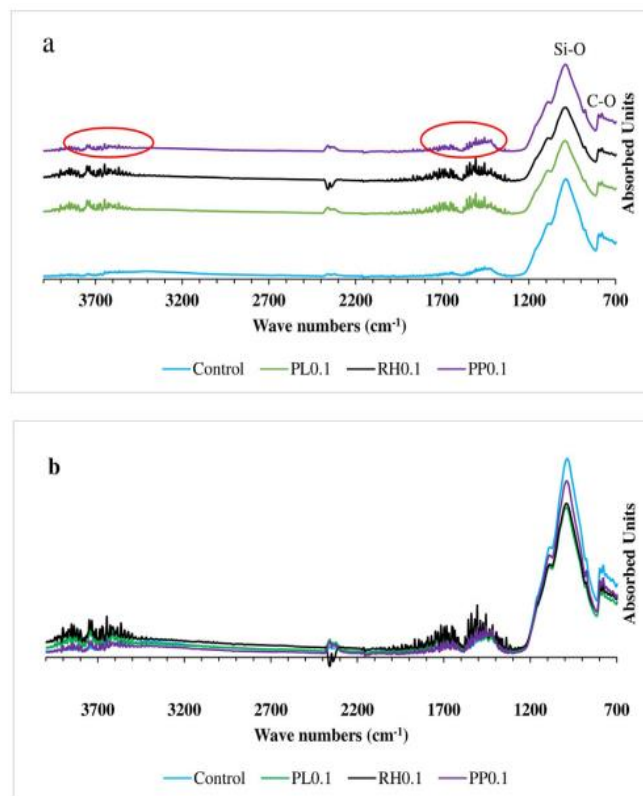


Figure 6: Result from FTIR test (Akhtar & Sarmah, 2018)

The result showed peaks at 781cm^{-1} and 980cm^{-1} which the authors assigned the C-O band and Si-O band. Those peaks according to the authors confirm the presence of calcium silicate hydrate C-S-H, here C-S-H is a common cement hydrator (Lothenbach et al., 2019). According to Horgnies et al. (2013), the C-S-H can shift due to aging and “according to the process of polymerization of the silica”. Horgnies et al. (2013) performed studies with different FTIR methods on cementitious materials. In the study, the authors analysed different materials. One of the materials analysed was Portlandite ($\text{Ca}(\text{OH})_2$) which gave a strong intensity at 3642cm^{-1} as seen in Figure 7 below

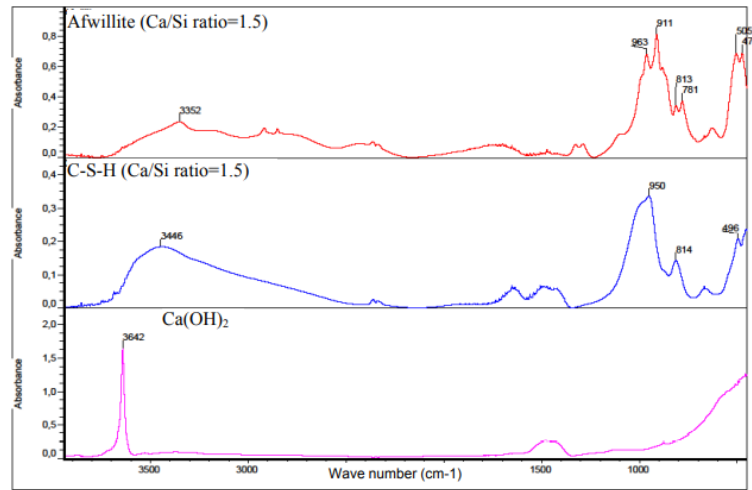


Figure 7: Results of IR spectra found by Horgnies et al. (2013)

Horgnies et al. (2013) also analysed the C-S-H, here the bond is not peaking at 781cm^{-1} which was found by Akhtar and Sarmah (2018), instead, there is noted that the characteristic peaks are located between 1100 and 900cm^{-1} . Yang & Wang (2021) analysed biochar through FTIR, the result of the test performed on the biochar is shown in Figure 8 below.

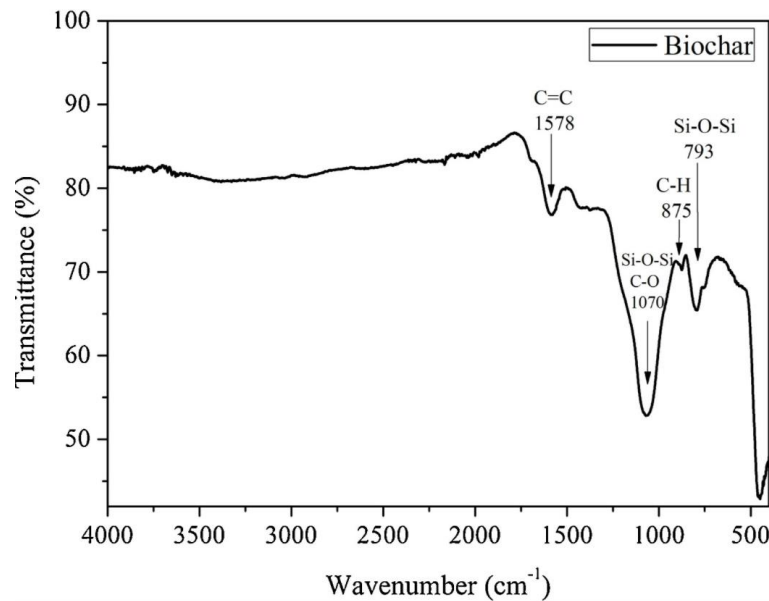


Figure 8: Result of FTIR test on biochar (X. Yang & Wang, 2021)

There can be seen points where the author detects a presence of silicone around 1070cm^{-1} and 793cm^{-1} . This corresponds to an analysis of biochar made from rice husk performed by Campos et al. (2020) where it was found that the composition of the biochar contained approximately 52% Silicone dioxide, 31% carbon, 14% ash, and other materials in smaller proportions such as ferrous oxide, potassium oxide, magnesium oxide and, calcium oxide.

2.3.6. Biochar in buildings and construction materials

The properties found in biochar could be used in building materials, not only according to mechanical properties and CO_2 sequences. Also, the biochar can return concrete which is less thermal conductive which would affect the total thermal efficiency of the building (Praneeth et al., 2021).

3. EXPERIMENTAL PROCEDURE

To examine the effects of adding biochar to concrete by replacing the cement an experimental study is done. Compared to previous studies where smaller proportions of cement (0.1–8 percent) have been replaced, this study aims to get a greater knowledge of what will happen to the structural properties of the concrete when larger proportions of biochar are added. This is based on the approach that the more the cement can be reduced from the concrete, the better the product will be concerning CO₂ emissions.

Although, if the biochar- concrete really should make an impact on the climate problems that we are facing, the material must be able to apply in larger structures.

The requirements of concrete manufacturing are high. According to the National Board of Housing, Building, and Planning's regulations, the concrete which is manufactured for use in constructions must be done by a person with documented education and or documented experience in concrete manufacturing and casting. However, the manufacturing should be done according to prescribed European standards. (Boverket, 2004)

To be able to calculate and design the structural element, the material properties must be determined. For concrete, various properties must be determined to applicate the material in structures. In this project, a selection has been done and the properties which will be determined are;

- Workability
- Density
- Compressive strength
- Chemical properties
- Microstructure

3.1.Procedure of testing according to Eurocode

The specimens in this thesis should be done as close as possible to the Swedish standard: SS-EN 12350-1:2019 – *Sampling and common apparatus*, SS-EN 12390-2:2019 – *Making and curing specimens for strength tests*, and SS-EN 12390-3:2019 – *Compressive strength of test specimens*.

The fresh concrete should be tested with a slump test where the slump test should be according to SS-EN 12350-2. The slump measurement is taken according to Figure 9 below. To be valid the shape of the sample should be according to Figure 9 a).

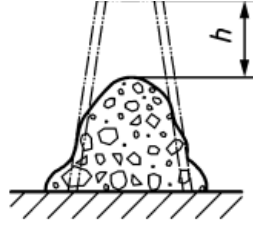
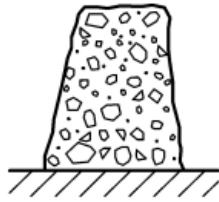
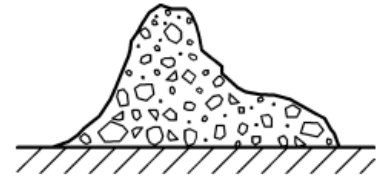


Figure 1 — Slump measurement



a) True slump



b) Shear slump

Figure 9: Forms of slump (SS-EN 12350-2:2019)

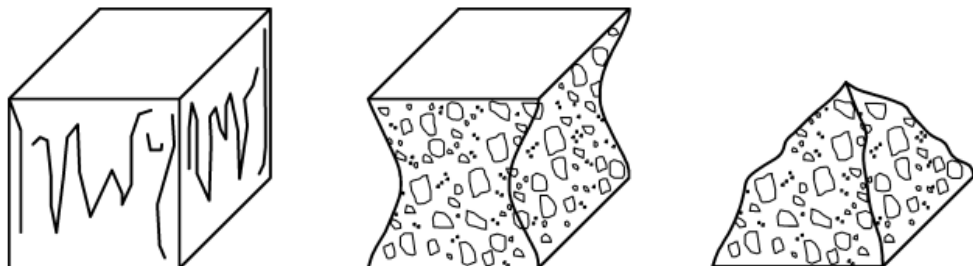
The slump should be measured and reported to closest the 10 mm according to SS-EN 12350-2:2019, section 9.g.

The bulk density for each sample is determined by measuring the volume of the specimen. The volume is measured by the average of two measurements of the side length and the height. The weight of the specimen is then noted, and the density is calculated as

$$\rho = \frac{m_s}{w \cdot l \cdot h} \quad [1]$$

The compressive strength should according to SS-EN 12390-3:2019 chapter 7.1 be tested as soon as possible from that the specimen is removed from curing. When the test is performed the cube should be placed with the loaded surface perpendicular to the side which the cube has been cast.

The shape of the sample after cracking is showing if the “tests have proceeded satisfactory”. A sample that deviates from this should be noted. In Figure 10 below there can be seen how the shape of a satisfactorily test should look alike. All exposed faces should have a similar crack pattern.



Explosive failure

Figure 10: Crack pattern of a satisfactorily performed test (SS-EN 12390-3:2019)

An example of how unsatisfactory failure could be visualized is presented in Figure 11 below.

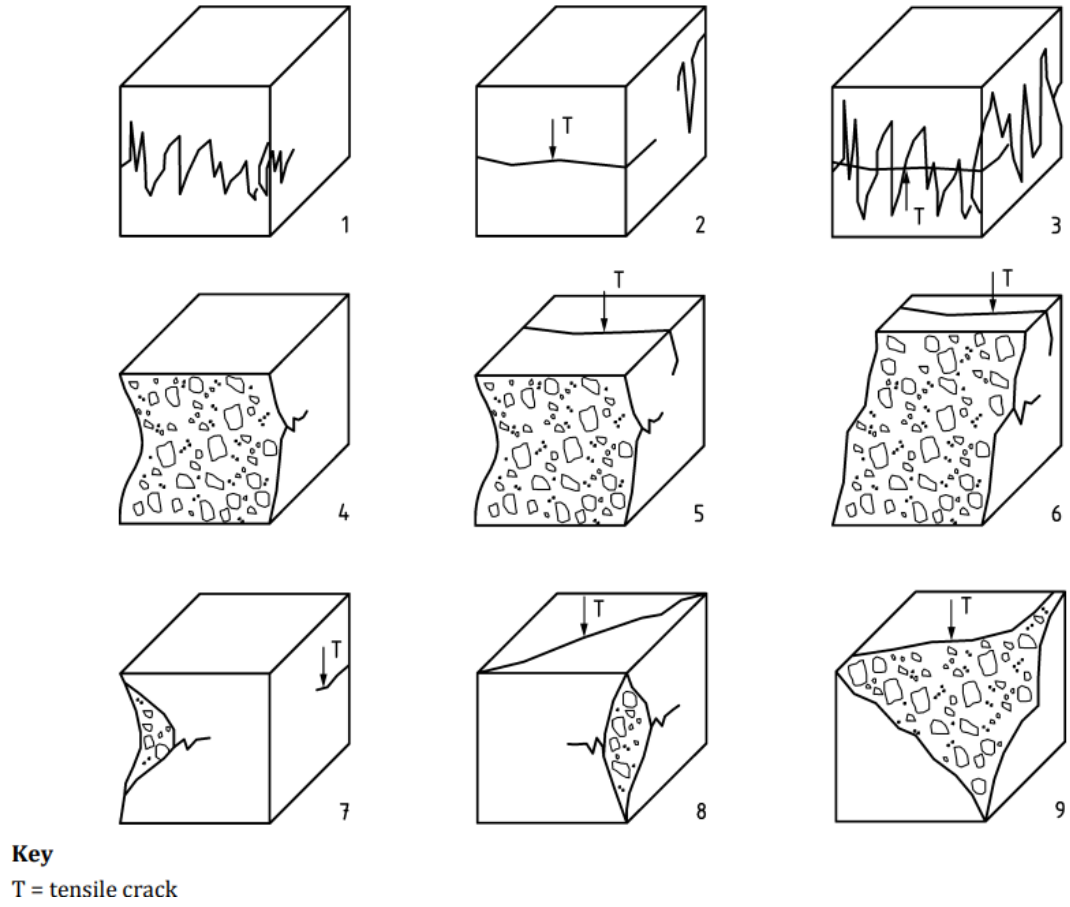


Figure 11: Unsatisfactory failure (SS-EN 12390-3:2019)

The compressive strength is then calculated according to

$$f_c = \frac{F}{A_c} \quad [2]$$

Where F is the failure load in N, A_c is the area of compression in mm and f_c is the compressive strength measured in MPa (N/mm²).

4. METHOD

The experimental study was performed with four individually mixed and cast batches where one of these is a control batch with a zero-percentage replacement. The control batch will act as a reference to compare the result of the test of the biochar-concrete samples. The ratio of the batches is 5, 8, and 10 percent exchange of the cement weight.

The recipe for the experimental tests is presented in Table 3 below, the recipe is provided from Cementa.

Table 3: Recipe of concrete mixtures

Mix ID	Water [kg]	Cement [kg]	Biochar [kg]	Aggregate 8-16 [kg]	Aggregate 0-8 [kg]	Master-glenium [kg]
0%	4.902	12.900	-	22.438	29.786	0.122
5%	4.755	12.255	0.645	22438.5	29.786	0.116
8%	4.667	11.868	1.032	22438.5	29.786	0.112
10%	4.608	11.610	1.290	22438.5	29.786	0.110

The recipe for the control batch follows the recipe mentioned above. For the mixes with a replacement of the cement with biochar, a correction has been done according to SS-EN 206:2013+A1:2016. According to the standard, the water to cement ratio can be adjusted due to an addition of fly ash with the factor k according to

$$w/cr = \frac{\text{water}}{\text{cement} + k \cdot \text{secondary binder}} \quad [3]$$

In the recipe above it has been assumed that the biochar has the same factor as fly ash. By adding the k -factor the water to cement ratio is slightly decreased according to its actual value.

From each mixture, 10 cubes and 2 cylinders will be cast, a total of 40 cubes and 8 cylinders. The first samples will be tested for their compressive strength after 28 days of curing in water. After additional 28 days, the rest of the cubes will be tested to see if there are any derivations due to further curing.

A slump test of the fresh concrete is done to determine the workability of the concrete before casting.

The biochar which is used in this paper comes from logging waste with a mixture of 90% softwood and 10% hardwood.

4.1. Experimental procedure

The experiment was proceeded in two steps, at first the control samples were cast and four weeks later the samples were tested. The biochar concrete was cast eight weeks after the control samples. This is mainly because of the lack of time and moulds for casting.

The samples were cast in 100 mm cubic moulds and cylindrical moulds with a diameter of $\varnothing$ 100 mm and a length of 200 mm. The cubic moulds were mainly made from rubber and the cylindrical moulds were made of steel. The materials used were 0–8 mm aggregate and 8–16 mm aggregate together with anläggningscement FA which is a Portland fly-ash cement manufactured at the Slite plant (Cementa, n.d.). The cement has a guiding value of 51 MPa after 28 days of curing.

4.1.1. Equipment

To measure the ingredients to the concrete mixture an ae Adam warrior scale is used with an accuracy of 0.01 kg. For the masterglenium and the weight of the cubes, a Sartorius scale with an accuracy of 0.0005 kg is used. The finer aggregates are placed in a micro-oven safe glass mould and dried in a normal micro-oven to denote the humidity. To mixture the aggregates before drying them, a concrete mixer (Figure 12) is used. The aggregates are stored in buckets with a lid before adding them to the mixer. To mix the concrete a Zyklos concrete mixer, model ZZ 75 HE (Figure 13) is used.

For the slump test, a hollow cone is used together with a funnel and a rod. The test is performed on a flat, portable quadratic metal plate. Scopes are used to fill the moulds which have been treated with a lubrication medium. The moulds have the metrics 100x100x100 for the cubic samples and $\varnothing$ 100x200 for the cylinders. The cubes are then tested for the compressive strength in a Toni Technik, hydraulic power unit model 2015 (Figure 19).

4.1.2. Material

The material which is used for the concrete mixture is “anläggningscement FA” from Cementa, this is a type of cement where the clinker ratio has been decreased to 80% and has an addition of fly ash and limestone. The cement has a 20 percent lower carbon dioxide emission according to a life cycle analysis than ordinary Anläggningscement, and this cement has a slower strength development compared to bas-cement and SH-cement (Cementa, n.d.). Further, 0–8 mm aggregate and 8–16 mm aggregate from Skanska’s source in Sunderbyn is used. The fluid medium which is used is MasterGlenium 592. Apart from this biochar from logging waste is used. The logging waste is containing about 90% softwood and 10% hardwood. More data is presented in Appendix A.

4.2. Preparation of the material

The aggregates required for the batches were collected by measuring the weight using an ae Adam warrior scale with an accuracy of 0.01 kg. The humidity of the two different aggregate types is determined by each specimen were mixed separately in a concrete mixer (Figure 12)

for a couple of minutes to ensure that the mix was uniform. The humidity of the aggregate is determined according to

$$w(\%) = 100 \cdot \frac{m_1 - m_2}{m_1} \quad [4]$$



Figure 12: Concrete mixture

The weight of the 0-8 mm aggregate was $m_1 = 1039.5$ grams after it had been dried in a micro-oven on full effect in approximately 5 minutes to remove moisture. The sample was then measured again. The dry weight was measured to $m_2 = 1039.0$ gram which means that the humidity of the aggregate could be determined to 0.14% for the 0-8 mm aggregate and the 8-16 mm aggregate did not show any water loss during drying which means that the humidity was approximately 0%.

The original recipe is adjusted according to the humidity of the aggregates. After the humidity is tested the required quantity of aggregates should be contained in such a way so that the humidity is constant. The casting which was planned to be done during the same week was done with two months separate in time. For the second casting, the aggregates were assumed to keep the same humidity as before since it was taken from the same storage.

The required amount of cement, water, and fluid medium for the baches is prepared before casting. The final recipe with measured ingredients is presented in the following chapter.

4.3. Mixing and casting of concrete

The dry ingredients were placed in the mixer with the fine aggregate in the bottom, then cement, and last the 8-16 mm aggregate. The dry ingredients were mixed shortly, it could be seen that the batch became too small for the mixer and would not be mixed properly because of this issue. The recipe was therefore doubled, and the extra dry ingredients were added in the same order as earlier, the dry ingredients and the mixer can be seen in Figure 13. The dry ingredients were mixed for one minute before the water was added together with 80% of the fluid medium and then it was mixed for about 2 minutes, here the concrete had a quite fluid consistency. The concrete was allowed to rest some while it got more stiffened. The rest of the fluid medium was added, and the mixer went for about 30 more seconds.



Figure 13: Mixture of dry ingredients

The second batch was cast about two months later. The humidity was assumed to remain since the aggregates were taken from the same source. The dry ingredients were first mixed for three minutes. Batch number two was doubled in the same manner as the first batch and then mixed for extensional two minutes. After this, the water was added together with the majority of the masterglenium. After adding the biochar to the mixture, the paste became significantly dryer compared to the mixture without biochar. The wet concrete was mixed for about two minutes, it could be seen that the consistency was quite dry. The rest of the masterglenium

was added while mixing to make the concrete more workable. The addition was mixed for about one extra minute.

Batch three and four were cast the day after batch two and were correctly measured at once. The cast followed the same procedure as for the second batch, but all the material was added at once. The outcome of the ingredients can be seen in Table 4 below.

Table 4: Actual recipe of casting

Mix ID	Water [kg]	Cement [kg]	Biochar [kg]	Aggregate [kg]	8-16 Aggregate [kg]	0-8 Masterglenium [kg]
0%	4.92	12.9	0	22.44	29.78	0.123
5%	4.75★	12.26★	0.65★	22.44	29.78	0.119
8%	5.08	11.88	1.03	22.44★	29.78★	0.114
10%	5.02	11.61	1.29	22.44★	29.78★	0.111

★ Estimated value due to lack of notations, no notations of changes were done during casting, it is presumed that required amount was used.

When the mixture was ready to cast a slump test was performed to examine the consistency of the concrete. As it had a fluid consistency half of the slump mould was filled and stroked with about 15 strokes and then the rest of it. It became clear that the concrete was quite fluid. Instead of taking the measurements of the height of the specimen the diagonal of the specimen was measured instead. After the slump test, the concrete was cast in cubes that had been lubricated to prevent the samples from getting stuck in the mould. The samples were compacted on a vibration board and covered with plastic. They were after this placed on a horizontal surface.

24 hours later the mould is removed, and the samples are immediately placed in a water tank to cure, the water is covering the cube entirely.

During the mixture of batch three and four, the mixture became too dry to be workable. An addition of 400g water was added. For batch four, the proportion of water was adjusted to the same water to cement ratio as for batch number three.

4.3.1. Slump test

A slump test of the fresh concrete was done. The control sample has the self-compacting property as there can be seen in Figure 14, the measurement of the spread diameter is therefore measured where the largest diameter can be found.



Figure 14: Spread of slump, 0% biochar addition

Since the concrete for the mixes with biochar replacement was thicker than the control samples (Figure 15), the slump test was performed according to standard.



Figure 15: Batch 3 after mixture

A third of the hollow cone was filled and struck 30 times with a rod, after this the next third was filled and struck. The third layer was then added. The hollow cone was struck 30 more times and after this, it was lifted strictly vertical, and the measurement of the height difference was measured. The measurement of the slump test was taken by placing one ruler towards the cone which was used to perform the test. A second ruler was then used to measure the distance between the height of the cone and the concrete as can be seen in Figure 16 below

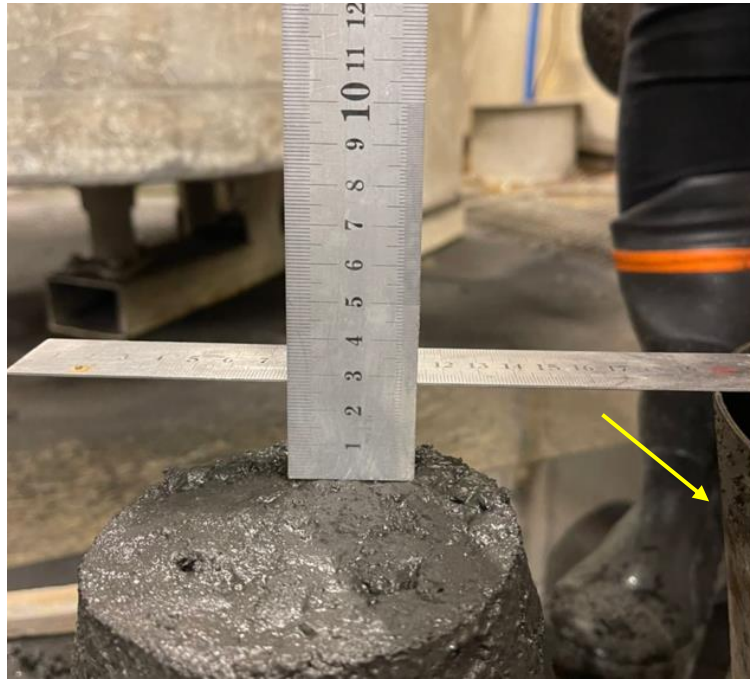


Figure 16: Set up for measuring the height of the slump test, arrow points on hollow cone.

4.3.2. Casting and curing

After the slump test is performed the concrete is cast in moulds. the samples were compacted with a vibration board which can be seen in Figure 17 below.



Figure 17: Compacting of the samples on a vibrating board. (Different test but same procedure, mould, and vibration board)

The samples were stored in the moulds for 24 hours. After this, the samples were placed for curing in wet conditions as seen in Figure 18. In the figure only batches 1-3 were placed for curing. Batch 4 was also added after this picture was taken.



Figure 18: Curing of batch 1-3

4.4. Testing of the samples

After curing 28 days the samples are tested for compressive strength. The test is performed with a 2015 Toni Technik with a testing speed of approximately 10kN/s.



Figure 19: Testing device for compressive strength

Each sample is marked on the side which is placed upwards in the test later. The cubes are measured in two places for each measurement and then divided by two to get a mean value which can be used to determine the volume of the specimen and the area of compressing. The area is calculated according to

$$A_{mean} = \frac{l_1+l_2}{2} \cdot \frac{d_1+d_2}{2} \quad [5]$$

Length, width, and height are measured with an electronic measurement tool with an accuracy of 0.01 mm. Each sample is weighted to decide the density. The cubes are tested for the compressive strength individually and the detected value is noted.

After additional 28 days (28+28) the second test of the cubes was done. The test was performed with the same procedure as before.

After the compressive strength is tested one sample of each batch is collected. Loose concrete is removed by hand to see the shape of the solid corpse.

4.5. Fourier-Transform Infrared

The FTIR test was performed according to the Attenuated Total Reflectance method, ATR method. The test was performed on two individual samples from one specimen of each replacement ratio. The samples were taken from the same cube but from different places, one from the side of the specimen and one from the middle. The material was ground mechanically by hand to obtain a finer material and make sure that the sample was mixed. The ground material was placed in two layers on the crystal surface to ensure that the sample was thick enough. The background spectra were collected to correct the test result. After this, the test was run with 16 scans per sample in the range between 600 and 4000cm⁻¹. Each sample was tested twice to ensure reliable results.

5. RESULTS AND ANALYSIS

The result from the experimental method is presented in the following chapter.

5.1. Fresh concrete

The control sample became fluid with self-compacting properties and spread out as can be seen in Figure 20 below. The measurement is taken of the largest diameter.



Figure 20: Slump test of control batch, 0% biochar

The ruler had a length of 600 mm. The measurement is taken of the largest side of the diameter which could be determined to be approximately 650 ± 5 mm. The consistency was not expected since the recipe used was not specified with this property. A slump-flow test according to SS-EN 12350-8:2019 should therefore be done. The spread measurement was determined but not according to the standard where the centre of the board should be marked with a cross to ensure that the cone is centred. The sample should not have been compacted, which in this case it was in the first layer of the filling. In the test only the largest diameter was measured, according to standard also the diameter of the right angle should be measured, which it was not.

Since the concrete changed consistency significantly when adding the biochar, the chosen method should not affect the result since there is not possible to compare the values between the concrete with 0% biochar and the concrete with biochar addition.

The slump test differed more between the 5 and 8 percent ratio than between the 8 and 10 percent ratio. For the 5 percent ratio, there could be seen a height difference of approximately 70 mm, the 8 percent sample showed a difference of 29 mm, and the 10 percent sample showed a difference of approximately 26 mm. A picture of the different measurements can be seen in Figure 21 below.

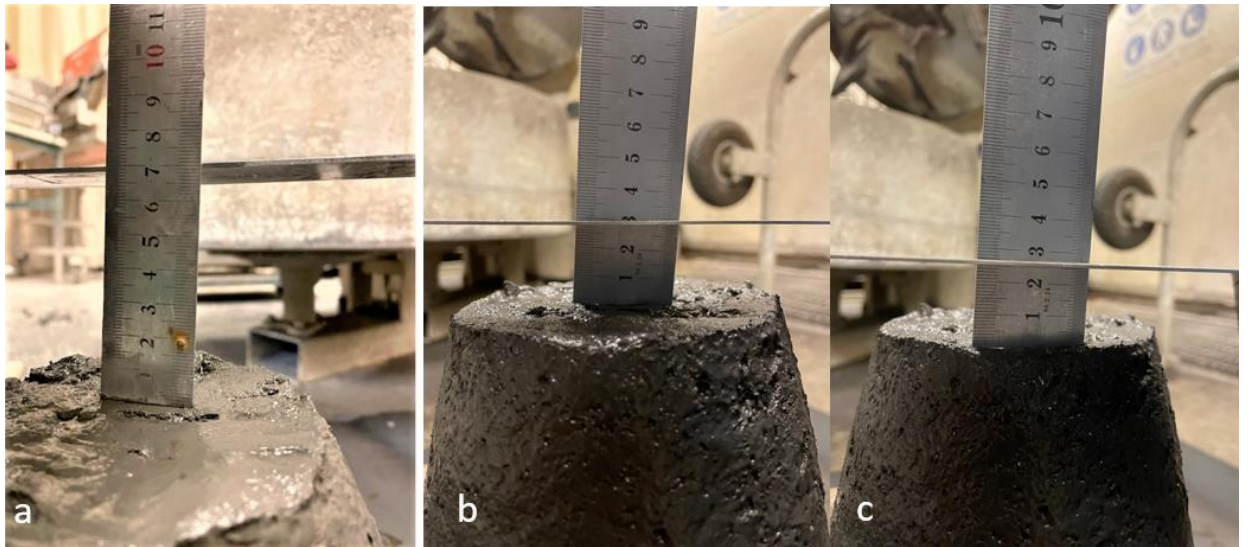


Figure 21: Slump test with height difference, a) 5% b) 8% c) 10% biochar

The result is presented in Table 5 below. The average is calculated from two different measurements of the height.

Table 5: Result from slump test

Mix ID	0%	5%	8%	10%
Measurement	[mm]			
1	650	69	30	25
2	-	70	29	26
Mean [mm]	650*	69.5	29.5	25.5

* Approximately value ± 50 mm

5.2.Density

The samples were measured and weighted. The data is presented in Table 6 below where the density has been calculated according to equation [1]. Test 1 has been cured for 28 days and test 2 for 56 days.

Table 6: Calculated density and average density of samples.

Mix ID	0%	5%	8%	10%	Mix ID	0%	5%	8%	10%
Test 1					Test 2				
Sample	[kg/m3]				Sample	[kg/m3]			
1	2410.5	2356.1	2326.2	2342.8	1	2389.1	2360.7	2370.8	2345.2
2	2423.5	2368.6	2354.8	2344.1	2	2407.8	2373.8	2353.2	2351.8
3	2413.6	2378.0	2369.5	2371.0	3	2440.0	2371.2	2353.0	2351.6
4	2432.9	2411.5	2345.9	2334.5	4	2415.8	2379.7	2360.1	2344.3
5	2419.9	2402.8	2376.5	2356.8	5	2425.1	2386.0	2360.7	2339.1
Average	2420.1	2383.4	2354.6	2349.8	-	2415.5	2374.3	2359.6	2346.4

There can be seen that the density is reduced when a part of the cement is replaced by biochar. The reduction of the density can be seen as linear when replacing up to 8 percent. An insignificant change is seen between 8 and 10 percent. A figure of the data can be seen in Figure 22 below, the values have been interpolated to create a figure with continuous values.

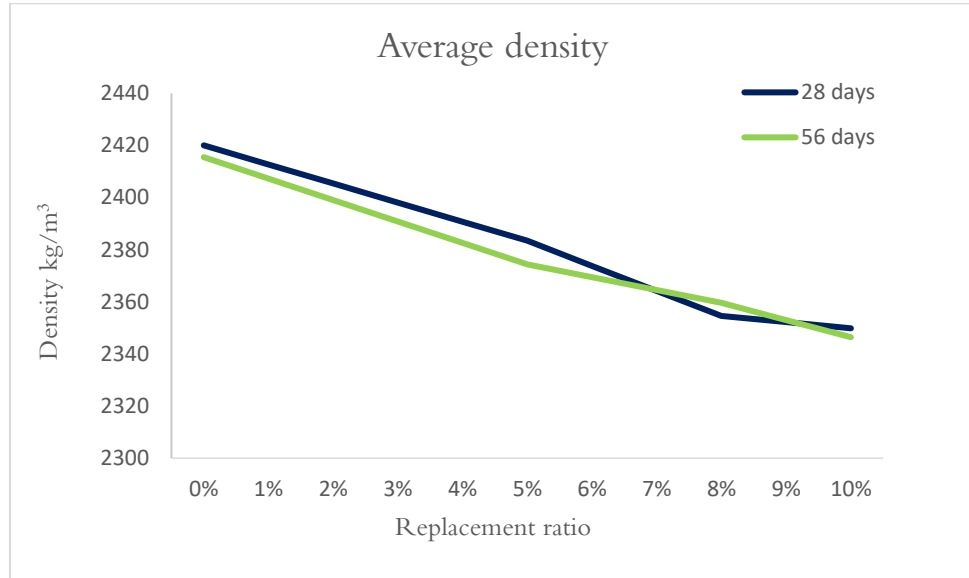


Figure 22: Average density of samples according to replacement ratio

The change in density is seen to decrease as the biochar ratio is increased. The result from 28 to 56 days of curing is corresponding to each other which indicates that the extra curing should not affect the density considerably.

The change in density could depend on the fact that biochar has a low bulk density due to its porous structure (Sirico et al., 2021), compared to cement.

The percental change is presented in Table 7 below. Compared to previous studies by Sirico et al. (2021) where a replacement ratio of 10 percent resulted in a lowered density with approximately 5 percent, here the value was lower. The difference could depend on the fact that the density of the biochar is depending on which source and pyrolysis process has been used.

Table 7: Percental change of density according to replacement ratio

Ratio	0%	5%	8%	10%
28 days	0.00%	1.52%	2.71%	2.90%
56 days	0.00%	1.71%	2.32%	2.86%

5.3. Compressive strength

The compressive strength is calculated through equation [2] based on the values from the failure load which is presented in Table 8, and the measurements of the compressed area. The calculated compressive strength is presented in Table 9.

Table 8: Detected failure load from compressive strength test.

Mix ID	0%	5%	8%	10%	Mix ID	0%	5%	8%	10%
28 days	N				56 days	N			
1	719000	712000	660000	719000	6	802000	802000	719000	606000
2	731000	713000	645000	731000	7	802000	770000	691000	616000
3	726000	683000	638000	726000	8	812000	772000	675000	595000
4	727000	709000	543000	727000	9	822000	775000	691000	595000
5	738000	763000	633000	738000	10	799000	801000	703000	591000
Average	728200	716000	623800	728200	-	807400	784000	695800	600600

Table 9: Calculated compressive strength for each sample and average.

Mix ID	0%	5%	8%	10%	Mix ID	0%	5%	8%	10%
28 days	MPa				56 days	MPa			
1	70.8	71.0	64.9	50.9	6	76.8	79.2	70.2	61.5
2	71.9	70.5	63.3	51.8	7	79.6	76.4	69.5	61.2
3	72.7	67.8	62.6	51.1	8	79.1	77.5	66.9	59.2
4	71.3	69.6	52.6	53.1	9	81.6	77.5	67.4	58.6
5	72.9	74.9	62.4	51.0	10	77.5	79.7	69.4	58.7
Average	71.9	70.8	61.2	51.6	-	78.9	78.1	68.7	59.8
%	0%	-1.6%	-14.9%	-28.3%		0.0%	-1.1%	-13.0%	-24.2%
% Change after additional 28 days						9.7%	10.3%	12.2%	16.0%

According to SS-EN 206:2013+A1:2016, classification is due to compressive strength. The classification could be determined for the cube strength. Since there has not been determined which cylindrical strength the samples obtain, the classification cannot be done according to Eurocode.

A visual presentation of the average values is also presented in Figure 23 below. This is to visualize the changes for compressive strength due to the added biochar ratio. Also, to visualize the difference between 28 and 56 days of curing. There should be noted that the change in ratio is smaller the higher the replacement is which gives an increased reduction with higher replacement ratios.

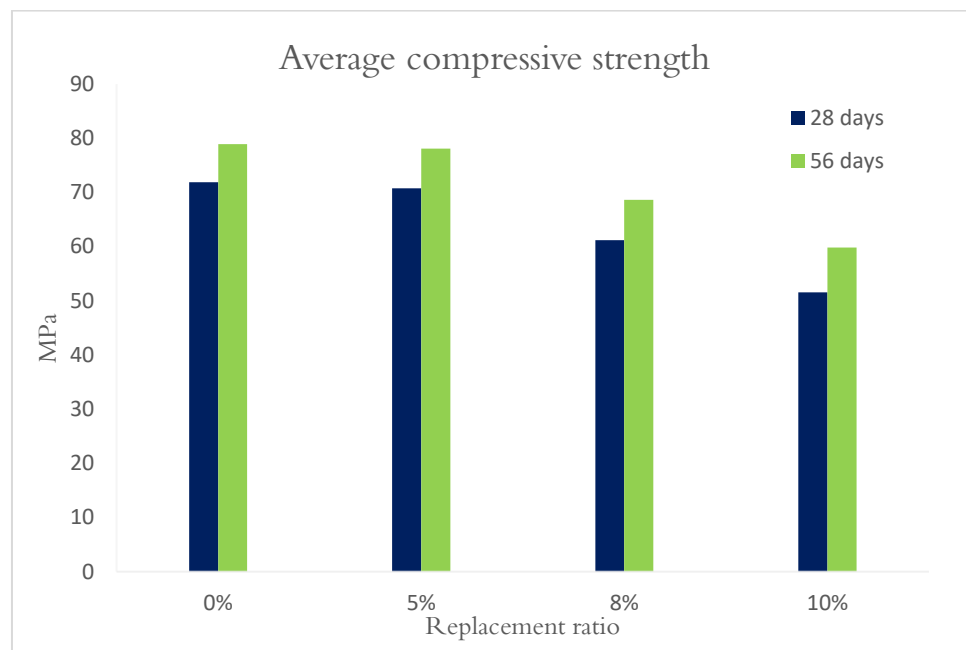


Figure 23: Average compressive strength

From the results, there can be seen that the strength is decreasing as the biochar ratio is increasing. Also, there can be seen that the strength after additional 28 days is increasing exponentially. This is also visualized in Figure 24 below.



Figure 24: Percental change from first to the second test

There can be seen that the compressive strength for the control sample increased around 10 percent while the mixture with 10 percent biochar increased by around 16 percent. This corresponds to the literature where it is claimed that concrete containing biochar is subjected to a second curing. It can be seen in the figure that the change between 5 and 8 percent replacement ratio gave about 2% increase in strength while there was an increase with about 4% between the 8 and 10 replacement ratios.

5.4. Cracking

The cracking due to testing of compressive strength can be seen in Appendix B where a picture of each tested cube after 28 days is presented. The cubes show a similar cracking pattern. After the loose concrete was removed from the cubes the shape could be clearer. One sample of each batch is presented in Figure 25 below.



Figure 25: Cubes after compression, 0 to 10 % from left.

Some of the cubes received cracks on the top and bottom of the cube. The cracks appeared on the same side which was subjected to the compression from the machine, a sample can be seen in Figure 26.

It is difficult to determine how the extensional curing of 28 days affected the crack pattern since the cracks in some cases are hard to notice.



Figure 26: Crack from compressive strength testing, top or bottom.

5.5. Fourier-Transform Infrared

Data was collected from the testing of the samples which was then converted to Excel and displayed as graphs. For a full result graph for each sample, see Appendix C.

In Figure 27 below the most intense result from each sample has been collected. A small difference can be seen around 2900cm^{-1} . This is most likely due to the organic content since the 2900 cm^{-1} matches the C-H stretching vibrations (Danial et al., 2015). Apart from this there is not seen any obvious divergency between the different samples which indicates that there is no different bonding in the concrete with biochar addition compared to the concrete without biochar. The highest peak can be seen around $950\text{--}1000\text{cm}^{-1}$.

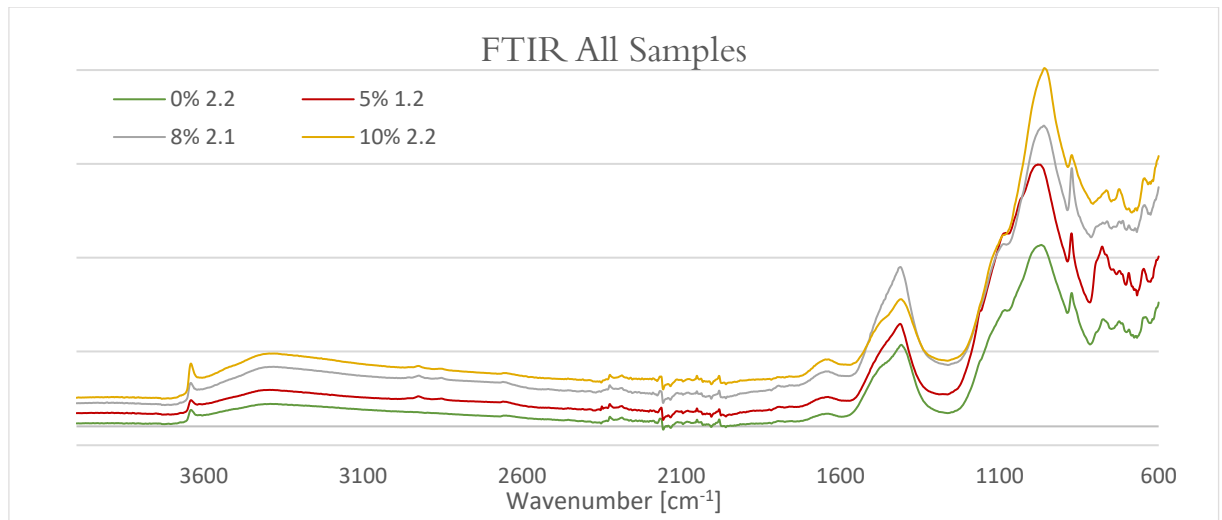


Figure 27: Result from FTIR, the highest intensity

As the material was scanned there could be seen that no other functional groups are present which indicates a pure carbon content in the biochar. A comparison to the literature review can be done where the result from the FTIR showed indications of silicone content (Figure 8).

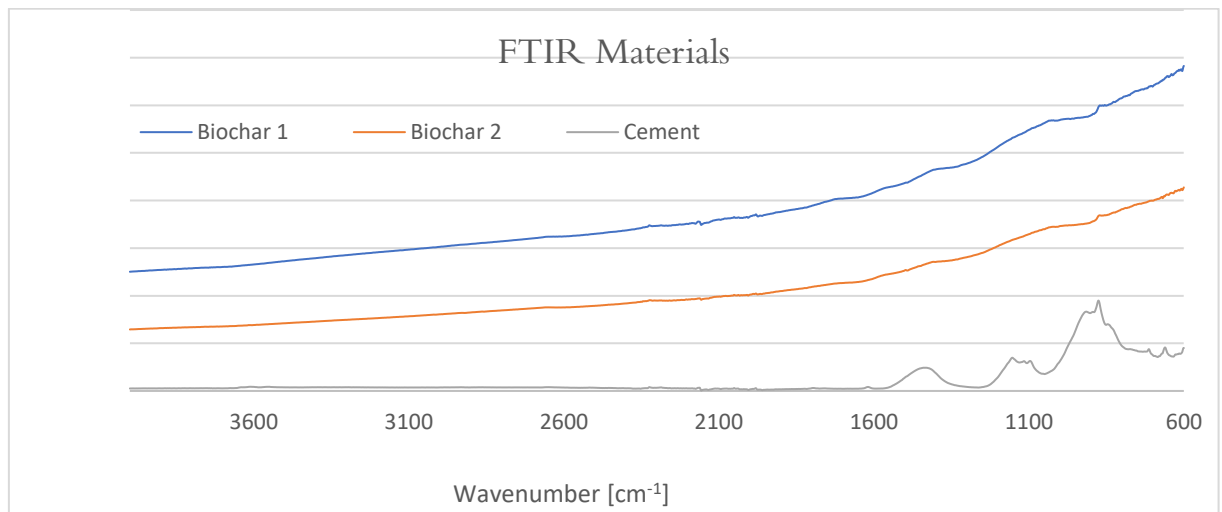


Figure 28: FTIR of cement and biochar samples

5.5.1. Scanning electron microscope

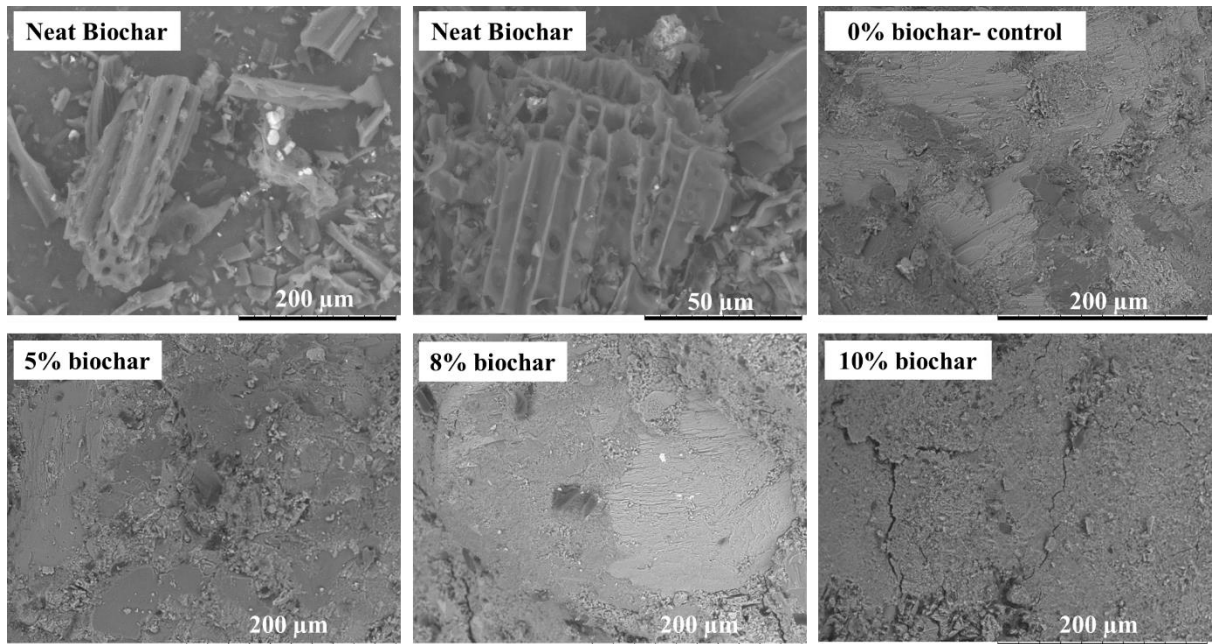


Figure 29: Microstructure of biochar and concrete.

A Hitachi TM 100 tabletop scanning electron microscope (SEM) was used with the voltage 22 kV and a current of 10 μ A to determine the microstructure of the concrete samples. The biochar, before being integrated into the concrete was also imaged. From the SEM images of biochar, the general size of the particles was ca. 100 μ m and some of them had porous structure, which is typical of wood-based biochar. Hydration of cement is an important process that contributed to the performance properties. In the compression strength tests, it was observed that with the increasing content of biochar in the samples, the strength increased in 56 days as compared to those of 28 days. Therefore, it can be assumed that hydration continued beyond 28 days. From the SEM micrographs, the control sample had disparity in the degree of hydration, observed by the different phases and the samples containing biochar, this disparity was lower, with the 10% sample having a uniform matrix. It is probable that the samples with a higher amount of biochar retained water in the pores that continued the hydration and thus curing of the concrete for a sustained period.

5.5.2. Carbon dioxide emissions

According to the recipe compared to the emission per tonne cement the emission reduction can be calculated. With the value of 0.94 tonnes of CO₂ per tonne cement and an assumption of biochar as carbon dioxide neutral the reduction per produced tonne of concrete can be reduced from 0.40 to 0.36 tonnes of CO₂ per produced cubic. To calculate the CO₂ emissions according to CO₂/ton the average density for the 28 and 56 days of curing has been used to determine the weight of 1m³ of concrete. However, it should be noted that the concrete would be reduced according to its compressive strength.

The carbon dioxide per cubic is calculated as

$$\frac{CO_2}{m^3} = m_{cem} \cdot 0.94$$

And the carbon dioxide per tonne is then calculated as

$$\frac{CO_2}{ton} = \frac{density}{\frac{CO_2}{m^3}}$$

Then the carbon dioxides per tonne concrete can be seen presented in Table 10 below

Table 10: Carbon emissions per cubic concrete

Volume: 1000 dm3					
Batch		0%	5%	8%	10%
Cement	[ton]	0.43	0.408	0.396	0.387
Biochar	[ton]	0	0.0215	0.344	0.430
Ballast <8mm	[ton]	0.99	0.99	0.99	0.99
ballast 8-16 mm	[ton]	0.75	0.75	0.75	0.75
Water (max)	[ton]	0.163	0.158	0.155	0.153
Weigh	[ton/m3]	2.42	2.38	2.36	2.35
CO2 per m3 conc.	[CO2/ m3]	0.40	0.38	0.37	0.36
CO2 per tonne concrete	[CO2/ton]	0.167	0.161	0.158	0.155
Reduction/ton	[CO2]	-	0.006	0.011	0.0013
Emission reduction from 20 billion tonnes concrete					
[billion ton]		0	0.115	0.188	0.245

This means that with 20 – 25 billion tons of concrete consumption each year ((Sirico et al., 2021)-(Gursel et al., 2014)), the carbon dioxide emissions could be lowered by 0.245 billion tonnes with a 10% cement replacement of biochar. this if the same mechanical properties can be obtained. If there is strength reduction in the concrete a higher volume is most likely to be needed. *Note that in this calculation example there is assumed that the emission from the biochar is equal to zero.*

6. DISCUSSION

From the result, there can be seen that the replacement ratio is affecting the properties of concrete regarding its workability, density, and compressive strength.

Workability

By adding biochar, the workability is highly affected by the biochar. This is most probably connected to the water-absorbing properties found in biochar. The workability is affected in such a way that for higher ratios, such as 8 and 10 percent replacement of the cement the concrete is perceived as dry. In this study, the addition of water was done to the mixture which could be a source of the lowered compressive strength since the strength is connected to the water to cement ratio. There could have been an addition of the fluid medium, masterglenium instead as Sirico et al. (2021) did in their experimental test where the superplasticiser was increased with the increased replacement ratio. The water to cement ratio was 0.38 for batch 1 and 2 (0 and 5% ratio) and 0.43 for batch 3 and 4 (8 and 10% replacement ratio). The biochar used in this project had a dry bulk density of 0.131 g/cm^3 (Appendix A). When replacing the cement according to its weight the volume of biochar became a lot larger than the volume of cement replaced. This could also impact the workability since it could be assumed that a larger proportion of small fraction material in the mixture would make the consistency thicker.

The k factor is changing the actual water to cement ratio slightly. Adding the k -factor allows us to add some extra water to the biochar where factor 0.4 is used in this thesis. In this case, further research could be necessary to see if the factor is valid for the biochar.

Density

The density could be seen to decrease while the ratio of biochar increased. As mentioned earlier the density of the biochar is relatively low in comparison to the cement which is approximately $1.25 \pm 0.25 \text{ g/cm}^3$ (Cementa, n.d.). Compared to each other the cement is 3.3 times the density of the biochar according to the result of Sirico et al. (2021) which was determined to be $0.38 \pm 0.01 \text{ g/cm}^3$. In comparison to the biochar in this thesis which had a density of 0.133 g/cm^3 . The result Sirico et al. (2021) presented is then diverging from the result in this thesis. The density decreased about 2.9 % in the concrete with a 10% replacement ratio while the density decreased by around 5% in the mixture with 10% replacement in the report of Sirico et al. (2021). This could mean that other factors from the density of the biochar could be essential to the density decreasing.

The decrease of the density is beneficial for concrete manufacturing where the energy consumption from transportation should be decreased with lower loads. Also, less heavy structures could be designed with lowered eigen weight.

Compressive strength

The compressive strength is decreasing as the biochar ratio is increasing which corresponds to the literature review. However, some of the previous studies showed that a 5 % replacement could give a higher strength, which was not found in this thesis. There is seen in Figure 23 that the change of reduction is increased with higher replacements of biochar. Regarding the result there should be remembered that the water to cement ratio was increased between the five- and eight percent ratio which is most likely affecting the compressive strength.

By comparing the results to the values in previous studies (Table 2) there can be seen that of biochar taken from wooden feedstock where the values are comparable. The replacement of 5% did show a decrease in this thesis, however, the decrease could be considered as low.

From the SEM results, the hypothesis that biochar benefits hydration has been proven by a more uniform matrix in the samples containing higher amounts of biochar. Thus, the pore structure of biochar can hold water and this excess water continues the curing of the cement for an extended period

The literature about compressive strength is diverging between different studies which makes it hard to compare to the results in this thesis. According to the findings, a reduction of the compressive strength was expected. There were not many studies that had been done to further cure, over 28 days which was an uncertainty to the expectation of the result. Some studies reported a second cure, but those studies were done to smaller proportions of biochar.

Crack pattern

A more detailed analysis of the crack pattern could have been done. This could have been used to see if there were any differences between the sample with and without biochar. Also, the shape of the remaining concrete after compressive testing could have been further investigated with a comparison of more of the samples.

FTIR

From the FTIR we could not find any chemical bonds which could affect the properties of the concrete with a biochar addition. This implies that the bonding that occurs in studies with lower percentages of biochar replacement should have mechanical properties. This could be due to mechanical interlocking (Das et al., 2016), or the fact that the crack pattern is changing (Ahmad et al., 2015), which could mean that greater energy is required to make it crack.

Carbon dioxide emissions

The calculations of carbon dioxide emission assume that the biochar is carbon neutral. However, according to the literature, the emission from biochar varies depending on the perspective of the analysis. The result is also only considering the reduction of emissions according to the reduction of cement to the mixture. Aspects according to a life cycle analysis

could affect this result. For example, the reduced density could lower the emissions from transportation due to reduced mass.

There can be seen from the results that with a 5% replacement of biochar to the concrete the compressive strength is affected only with -1.6%. This finding is considered promising since even small proportions of biochar can make a large impression on the carbon dioxide emissions and still not affect the compressive strength to a great extent.

Miscellaneous

As there was found in the literature that the flexural strength was increasing when adding the biochar, it would have been interesting to investigate this with the samples provided in this paper. The paper which has covered this subject has added slightly lower content, except from Praneeth et al. (2021) which found an increment up to 20 percent replacement ratio.

Another property that should be analysed is the modulus of elasticity which is essential to be able to apply the material to structural elements. In this thesis, there was an aim to determine the properties of the concrete. This could not be done, mainly because of a lack of time and planning.

7. CONCLUSION

The workability of the concrete is affected when adding biochar to the mixture. There could be seen that significant changes appeared in the mixture where the constancy went from fluid to compact when the biochar was added to the mixture.

The addition of higher content of biochar is most likely to decrease the compressive strength in concrete. This could be seen both in the literature and in the result of this thesis. However smaller portions of biochar could according to the literature increase the compressive strength, with decreasing values with higher proportions.

There cannot be seen any chemical bonding through the FTIR test of biochar to cement. No significant results could be found from the FTIR which implies that the change in properties is due to mechanical properties.

By adding biochar to concrete the compressive strength is increasing when the specimen is allowed to cure during longer periods. This is not to be seen as the compressive strength is increased compared to concrete without biochar, which in this thesis was found to be higher. What this means is that the compressive strength is continuing to develop even after 28 days where concrete without biochar has a lower growth.

The bulk density of the specimen is decreasing while the biochar ratio is increasing. This is most likely because of the lower density of biochar.

The crack pattern is not majorly affected, there could be some less divergence with a longer curing period. However, a more detailed analysis could give other results.

When adding biochar to concrete the carbon emissions can be reduced. If the biochar addition does not negatively affect the properties of the concrete, then the high carbon footprint cement can be replaced thereby reducing CO₂ emissions. The total production of concrete is so large that small changes can have a large impact.

The literature and the results found in this thesis are comparable to each other. The compressive strength is diverging highly between studies. However, there can be seen that the behaviour of the biochar could in some cases be predictable, especially for the workability, however, the compressive strength is more likely to differ.

All together the result shows that the replacement of cement with biochar could be a solution to some of the carbon emission issues of concrete in the future. There could be seen that the compressive strength had a small difference when the control sample was compared to the 5% ratio sample. Also, promising results were obtained according to the additional strength development beyond 28 days of curing. Although, the negative effect of the workability is something that could be an issue since stiff concrete is less usable in the reality.

Further research

In this thesis, a selection of tests according to Eurocode has been adapted. For further research, extended testing should be done. Both for fresh and cured concrete. This is to further analyse the property changes in concrete due to biochar applications.

The water retraining properties of biochar in concrete mixtures should be valuated to determine a coefficient to adjust the water to cement ratio.

Also, the long-term effect of biochar concrete exposed to real-life conditions should be examined.

To be able to get a grip of how the material would work in structural elements, the modulus of elasticity should be determined, and the cylindric compressive strength.

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i. Appendix A



Report number : AR-20-FR-038684-02
Page 1 of 6

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This report replaces the previous report AR-20-FR-038684-01 from 2020-11-19.

Title : **Test report for order 12039671**
Test report number : **AR-20-FR-038684-02**

Project name : **Biochar ba-de-30-1-2**

Number of samples : **1**
Sample type: **biochar**
Sample Taker: **Client**

Sample reception date : **2020-11-02**
Sample processing time : **2020-11-02 - 2020-11-19**

The test results refer solely to the analysed test specimen. Unless the sampling was done by our laboratory or in our sub-order the responsibility for the correctness of the sampling is disclaimed. This test report is only valid with signature and may only be further published completely and unchanged. Extracts or changes require the authorisation of the EUROFINS UMWELT in each individual case.

Our General Terms & Conditions of Sale (GTCS) are applicable, as far as no specific agreements do exist. The GTCS are available on <http://www.eurofins.de/umwelt/avb.aspx>.

Accredited test laboratory according to DIN EN ISO/IEC 17025:2018 DAkkS notification under the DAkkS German Accreditation System for Testing. The laboratory is according (D-PL-14081-01-00) accredited.

Attachments
12039671_120149290_Azoxypin_FA

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Kto 7000000550
IBAN DE27 2073 0017 7000 0005 50
BICSWIFT HYVEDE33MEE17

ii. Appendix B

0% Biochar replacement, 28 days curing



Figure 30: Cubes after compression, batch 1 test 1, test 2

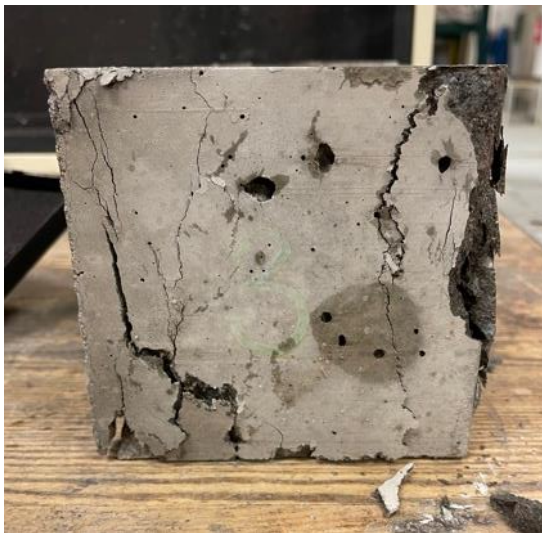


Figure 31: Cubes after compression, batch 1 test 3, test 4



Figure 32: Cube after compression, batch 1 test 5

5% biochar replacement



Figure 33: Cube after compression, batch 2 test 1



Figure 34: Cube after compression, batch test 2



Figure 35: Cube after compression, batch 2 test 3



Figure 36: Cube after compression, batch 2 test 4



Figure 37: Cube after compression, batch 2 test 5

8% Biochar replacement



Figure 38: Cube after compression, batch 3 test 1



Figure 39: Cube after compression, batch 3 test 2, test 3



Figure 40: Cube after compression, batch 3 test 4



Figure 41: Cube after compression, batch 3 test 5

Replacement ratio 10%



Figure 42: Cube after compression, batch 4 test 1



Figure 43: Cube after compression, batch 4 test 2



Figure 44: Cube after compression, batch 4 test 3



Figure 45: Cube after compression, batch 4 test 4



Figure 46: Cube after compression, batch 4 test 5

56 days of curing

0% biochar



Figure 47: Cube after compression, divergent cracking.

5% biochar



Figure 48: Cube after compression, batch 2 test 1 (56 days)



Figure 49: Cube after compression, batch 2 test 2 (56 days)



Figure 50: Cube after compression, batch 2 test 3 (56 days)



Figure 51: Cube after compression, batch 2 test 4 (56 days)



Figure 52: Cube after compression, batch 2 test 5 (56 days)

8 % Biochar



Figure 53: Cube after compression, batch 3 test 1 (56 days)

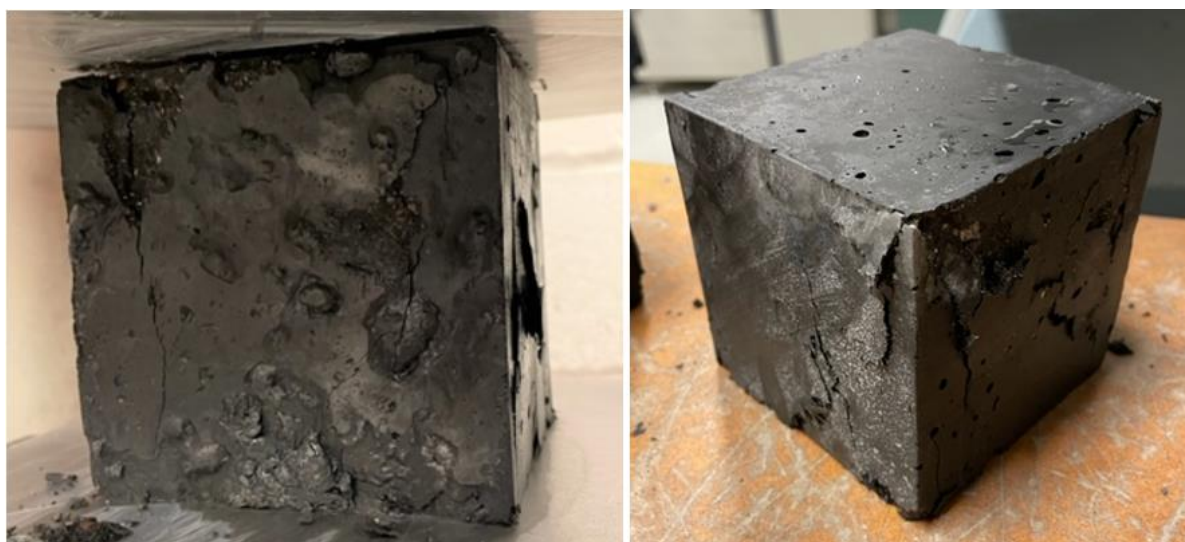


Figure 54: Cube after compression, batch 3 test 2 (56 days)



Figure 55: Cube after compression, batch 3 test 3 (56 days)



Figure 56: Cube after compression, batch 3 test 4 (56 days)



Figure 57: Cube after compression, batch 3 test 5 (56 days)

10% Biochar



Figure 58: Cube after compression, batch 4 test 1 (56 days)



Figure 59: Cube after compression, batch 4 test 2 (56 days)



Figure 60: Cube after compression, batch 4 test 3 (56 days)



Figure 61: Cube after compression, batch 4 test 4 (56 days)

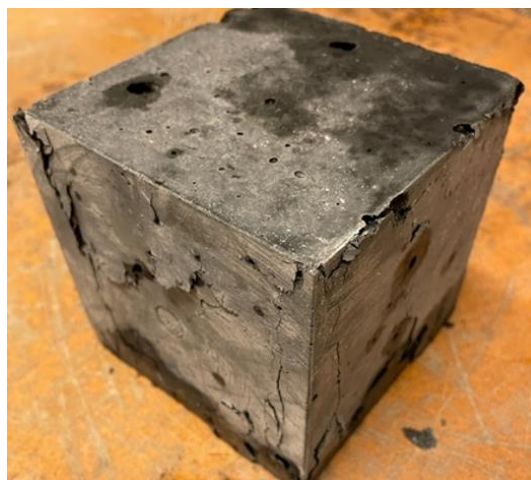


Figure 62: Cube after compression, batch 4 test 5 (56 days)

iii. Appendix C

FTIR

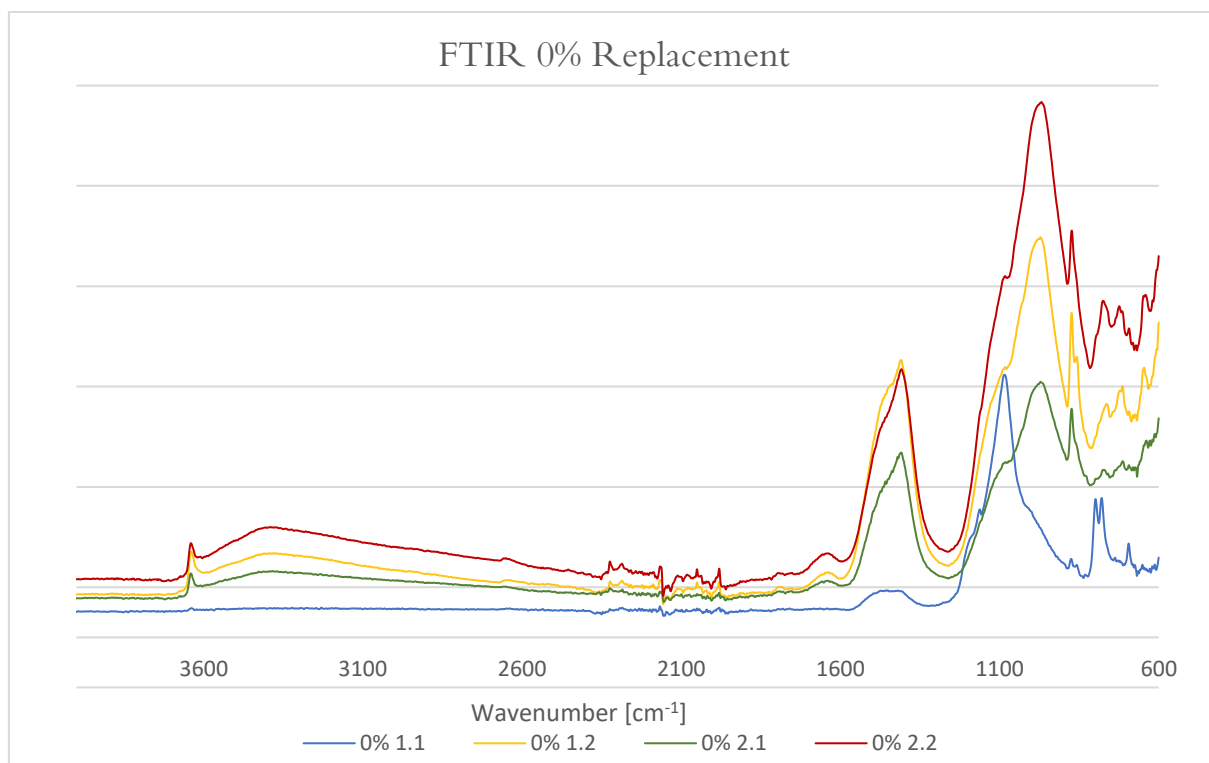


Figure 63: FTIR all tests 0%

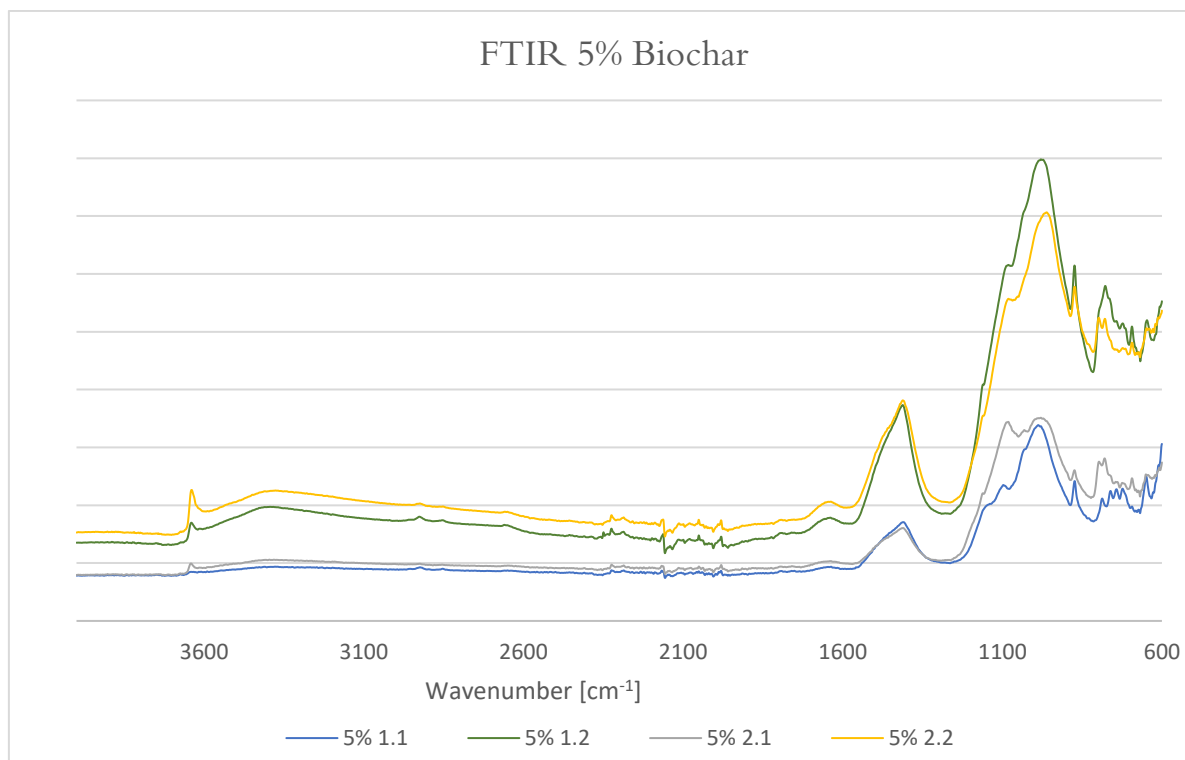


Figure 64: FTIR all tests 5%

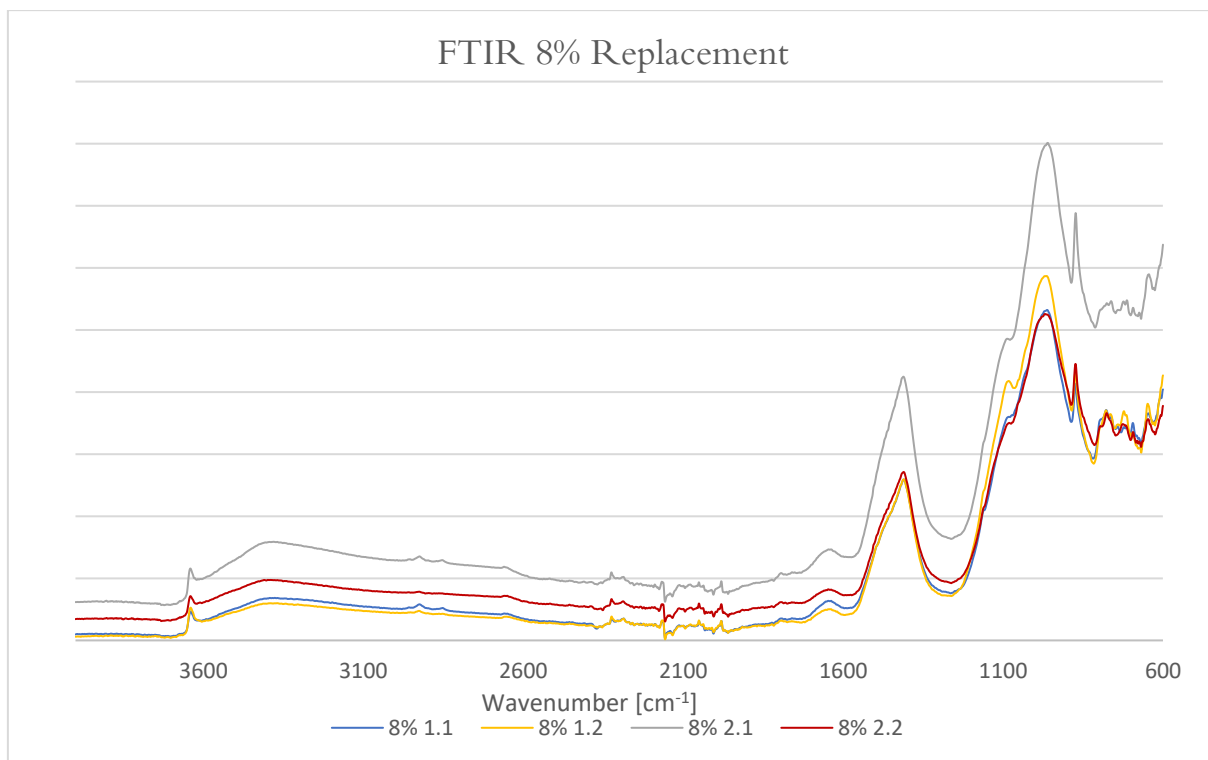


Figure 65: FTIR all tests 8%

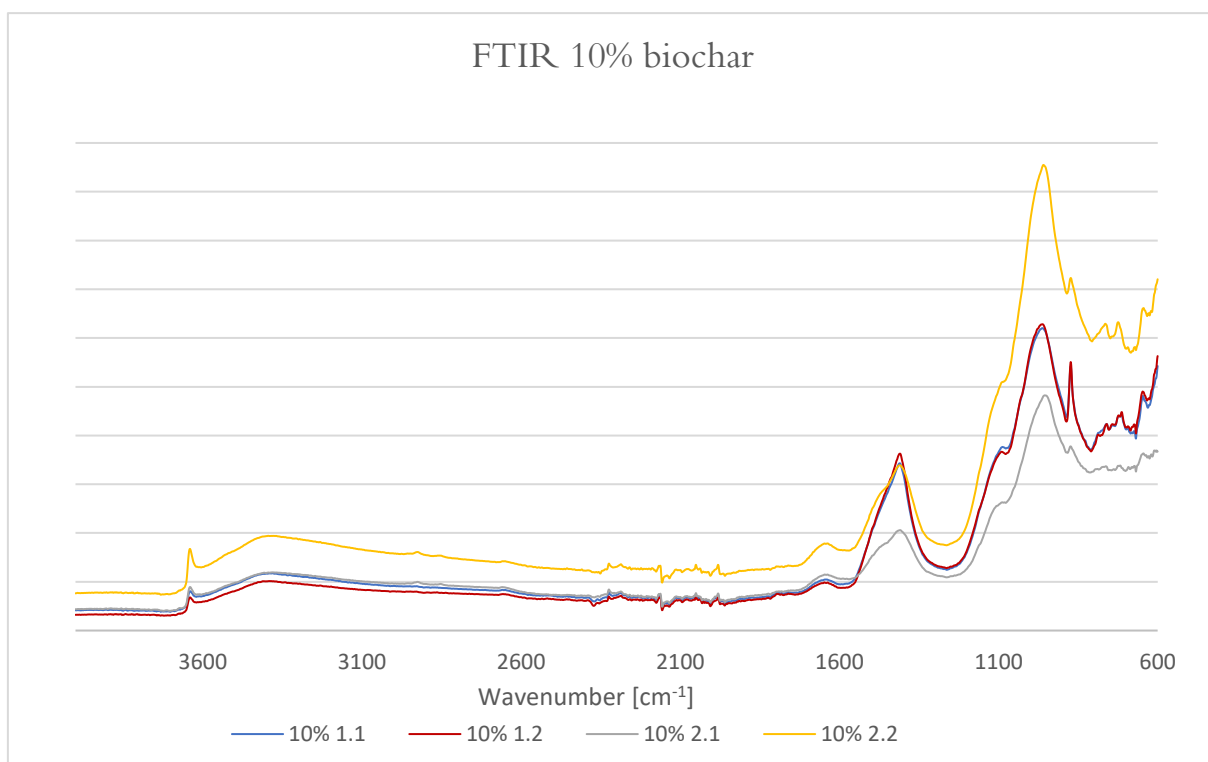


Figure 66: FTIR All tests 8%

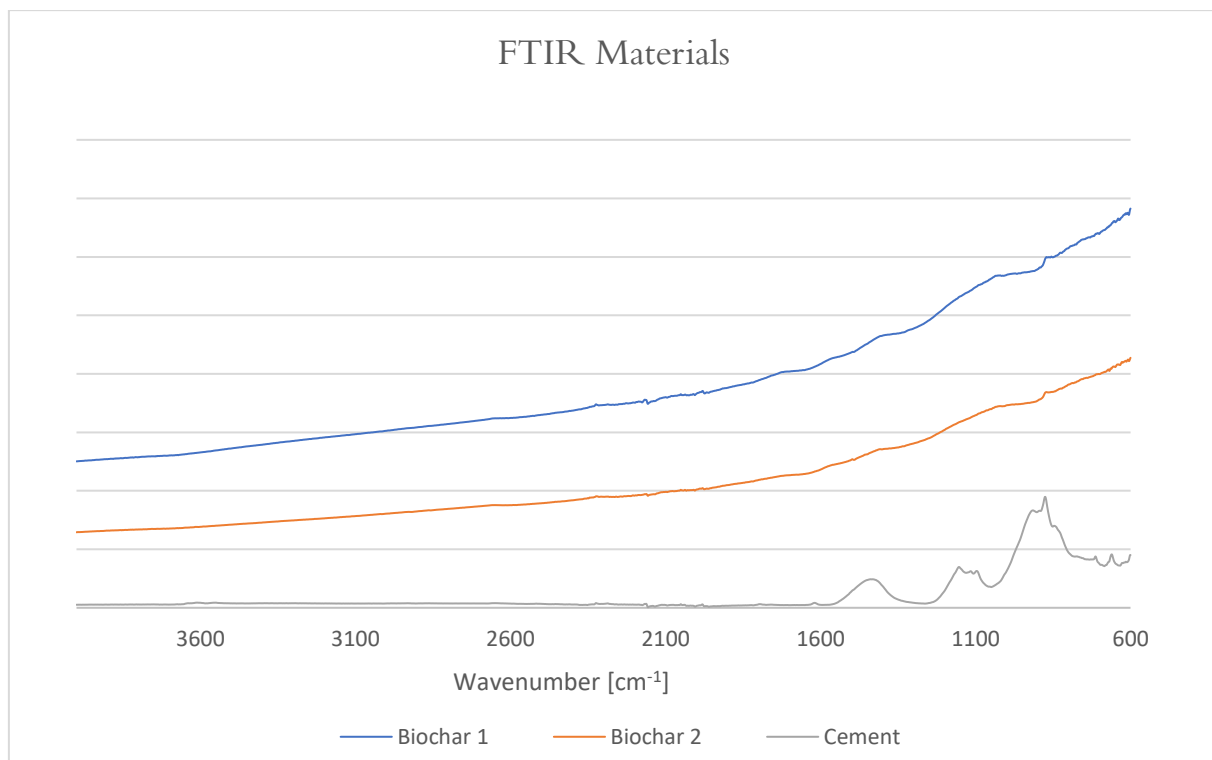


Figure 67: FTIR of cement and biochar